THE MISSISSIPPIAN LEADVILLE LIMESTONE EXPLORATION PLAY, UTAH AND COLORADO – EXPLORATION TECHNIQUES AND STUDIES FOR INDEPENDENTS

SEMI-ANNUAL TECHNICAL PROGRESS REPORT October 1, 2005 - March 31, 2006

by

Thomas C. Chidsey, Jr., Principal Investigator/Program Manager,
J. Wallace Gwynn, Craig D. Morgan and Michael D. Vanden Berg,
Utah Geological Survey,
and
David Seneshen, Direct Geochemical

UTAH DNR GEOLOGICAL SURVEY

August 2006

Contract No. DE-FC26-03NT15424

Virginia Weyland, Contract Manager
U.S. Department of Energy
National Petroleum Technology Office
Williams Center Tower One
1 West 3rd Street
Tulsa, OK 74103-3519

DISCLAIMER

THE MISSISSIPPIAN LEADVILLE LIMESTONE EXPLORATION PLAY, UTAH AND COLORADO – EXPLORATION TECHNIQUES AND STUDIES FOR INDEPENDENTS

SEMI-ANNUAL TECHNICAL PROGRESS REPORT October 1, 2005 - March 31, 2006

by

Thomas C. Chidsey, Jr., Principal Investigator/Program Manager,
J. Wallace Gwynn, Craig D. Morgan and Michael D. Vanden Berg,
Utah Geological Survey,
and
David Seneshen, Direct Geochemical

Date of Report: August 2006

Contract No. DE-FC26-03NT15424

Virginia Weyland, Contract Manager
U.S. Department of Energy
National Petroleum Technology Office
Williams Center Tower One
1 West 3rd Street
Tulsa, OK 74103-3519

Submitting Organization: Utah Geological Survey
1594 West North Temple, Suite 3110
P.O. Box 146100
Salt Lake City, Utah 84114-6100
Ph.: (801) 537-3300/Fax: (801) 537-3400

ABSTRACT

The Mississippian Leadville Limestone is a shallow, open-marine, carbonate-shelf deposit. The Leadville has produced over 53 million barrels (8.4 million m^3) of oil from six fields in the Paradox fold and fault belt of the Paradox Basin, Utah and Colorado. The environmentally sensitive, 7500-square-mile (19,400 km^2) area that makes up the fold and fault belt is relatively unexplored. Only independent producers operate and continue to hunt for Leadville oil targets in the region. The overall goal of this study is to assist these independents by (1) developing and demonstrating techniques and exploration methods never tried on the Leadville, (2) targeting areas for exploration, and (3) conducting a detailed reservoir characterization study. The final results will hopefully reduce exploration costs and risks, especially in environmentally sensitive areas, and add new oil discoveries and reserves.

This report covers research and technology transfer activities for the first half of the third project year (October 1, 2005, through March 31, 2006), Budget Period II. This work consisted of (1) describing Paleozoic brine chemistry and regional trends in the Paradox Basin, and (2) conducting a surface geochemical survey over the Lisbon case-study field area, Utah.

There is a systematic change in the chemistry of both the Mississippian/Devonian- and Pennsylvanian-brine systems from north to south through the Paradox Basin. The Pennsylvanian-system brines are more saline than the Mississippian/Devonian-system brines. Bicarbonate is very low in both brine systems. The direction of ground-water movement in the Mississippian/Devonian and Pennsylvanian systems is generally southwestward.

Lisbon field is ideal for a surface geochemical survey because proven hydrocarbons underlie underlie the area, it is easily accessible, and the surface geology is similar to the structure of the field. Proving the success of relatively low-cost geochemical surveys at Lisbon field will allow independent operators to reduce risks and minimize impacts on environmentally sensitive areas while exploring for Leadville targets.

The Lisbon field geochemical survey consisted of collecting shallow soil samples over and and around the field covering the oil-leg, gas cap, and background "barren" areas to map the spatial distribution of potential surface hydrocarbon anomalies. In addition, samples were collected over oil, gas, and dry wells for analogue matching purposes and to refine the discriminant model for Lisbon field. As of March 31, 2006, a total of 160 samples had been collected by the UGS along the sampling grid. Samples are being dried and sieved, and aliquots are now being weighed out for chemical analyses for 40 hydrocarbon compounds in the C_l-C_{12} range, 53 major and trace elements, seven anion species, and for Synchronous Scanned Fluorescence analyses. Sample results will be plotted and contoured to identify any surficial geochemical anomalies.

Joints in exposures of the Navajo and Entrada Sandstones may provide pathways for hydrocarbon microseepage to the surface. We recommend expanding the sampling program to collect the sand and lichen from the joints for hydrocarbon and elemental analysis over barren and productive parts of Lisbon field.

To the southwest, the recently discovered Lisbon South field has similar geology to Lisbon field. However, the field is still near original reservoir pressure and therefore hydrocarbon microseepage to the surface may be more significant than at Lisbon field. We also recommend an additional expansion of the surface geochemical survey to include this new field area.

Technology transfer activities for the reporting period consisted of technical presentations on Leadville characteristics and dolomitization, and publications. The project home page was updated on the Utah Geological Survey Web site.

CONTENTS

FIGURES

TABLES

EXECUTIVE SUMMARY

The Mississippian Leadville Limestone is a shallow, open-marine, carbonate-shelf deposit. The Leadville has produced over 53 million barrels (8.4 million m^3) of oil from six fields in the Paradox fold and fault belt of the Paradox Basin, Utah and Colorado. These fields are currently operated by small, independent producers. The environmentally sensitive, 7500-square-mile (19,400 km^2) area that makes up the fold and fault belt is relatively unexplored. Only independent operators continue to hunt for Leadville oil targets in the region. The overall goal of this study is to assist these independents by (1) developing and demonstrating techniques and exploration methods never tried on the Leadville Limestone, (2) targeting areas for exploration, and (3) conducting a detailed reservoir characterization study. The final results will hopefully reduce exploration costs and risk especially in environmentally sensitive areas, and add new oil discoveries and reserves.

To achieve this goal and carry out the Leadville Limestone study, the Utah Geological Survey (UGS) and Eby Petrography & Consulting, Inc., have entered into a cooperative agreement with the U.S. Department of Energy (DOE), National Petroleum Technology Office, Tulsa, Oklahoma. The research is funded as part of the DOE Advanced and Key Oilfield Technologies for Independents (Area 2 – Exploration) Program. This report covers research and technology transfer activities for the first half of the third project year (October 1, 2005, through March 31, 2006), Budget Period II. This work consisted of (1) describing Paleozoic brine chemistry and regional trends in the Paradox Basin, and (2) conducting a surface geochemical survey over the Lisbon case-study field area, Utah.

There is a systematic change in the chemistry of both the Mississippian/ Devonian and Pennsylvanian brine systems from north to south through the Paradox Basin, and the associated counties. The Pennsylvanian-system brines are more saline than the Mississippian/Devonian-system brines. Piper and Stiff diagrams show that the brines from both systems are highly sodium-rich in nature, with some samples containing greater percentages of calcium and to a lesser extent magnesium. The Piper and Stiff diagrams also show that both brine systems are high in chloride, but some samples have increased sulfate content. Bicarbonate is very low in both brine systems. The direction of ground-water movement in the Mississippian/Devonian and Pennsylvanian systems is generally southwestward toward the topographically low outcrop areas along the Colorado River in Arizona.

Surface geochemical surveys have proved helpful in identifying areas of poorly drained or by-passed oil in other basins. Lisbon field is ideal for a surface geochemical survey because proven hydrocarbons underlie the area, it is easily accessible, and the surface geology is similar to the structure of the field. Lisbon field is the largest Leadville producer in Utah and is still actively producing oil and gas. The surface geology at Lisbon field consists of a major anticline along a large normal fault. Proving the success of relatively low-cost geochemical surveys at Lisbon field will allow independent operators to reduce risks and minimize impacts on environmentally sensitive areas while exploring for Leadville targets.

The geochemical survey consisted of collecting about 200 shallow soil samples at 1500-foot intervals (500 m) over and around the Lisbon field on a 16-square-mile (42 km^2) rectangular grid to map the spatial distribution of potential surface hydrocarbon anomalies. The sampling grid extends beyond the proven limits of Lisbon field to establish background readings. The area chosen sufficiently covers the oil-leg, gas cap, and background "barren" areas. In addition, samples were collected over oil, gas, and dry wells for analogue matching purposes and to refine the discriminant model for Lisbon field.

Ninety samples were collected around productive oil (two) wells in the oil leg, gas (two) wells in the gas cap, and two barren dry wells; 15 samples at each well site. As of March 31, 2006, a total of 160 samples had been collected by the UGS along the sampling grid. Samples are being dried and sieved, and aliquots are now being weighed out for chemical analyses for 40 hydrocarbon compounds in the C_1-C_{12} range, 53 major and trace elements, seven anion species, and for Synchronous Scanned Fluorescence analyses. Sample results will be plotted and contoured to identify any surficial geochemical anomalies.

Joints in exposures of the Navajo and Entrada Sandstones may provide pathways for hydrocarbon microseepage to the surface. We recommend expanding the sampling program to collect the sand and lichen from the joints for hydrocarbon and elemental analysis over barren and productive parts of Lisbon field.

To the southwest, the recently discovered Lisbon South field has similar geology to Lisbon field, both in terms of structure and a Leadville reservoir. It consists of two producing wells, primarily gas and condensate, along with barren dry wells off structure. However, the field is still near original reservoir pressure and therefore hydrocarbon microseepage to the surface may be more significant than at Lisbon field. We also recommend an additional expansion of the surface geochemical survey to include this new field and the surrounding area.

Technology transfer activities for the reporting period consisted of technical presentations and publications. The presentations, made at the Fort Worth Geological Society monthly meeting, October 10, 2005, in Fort Worth, Texas, and at the Geological Society of America Annual Meeting, October 16, 2005, in Salt Lake City, Utah, described Leadville characteristics and diagenesis with emphasis on dolomitization. The project home page was updated on the Utah Geological Survey Web site.

INTRODUCTION

Project Overview

The Mississippian Leadville Limestone has produced over 53 million barrels (bbls) (8.4 million m^3) of oil from six fields in the northern Paradox Basin region, referred to as the Paradox fold and fault belt, of Utah and Colorado. All of these fields are currently operated by small, independent producers. There have been no new discoveries since the early 1960s, and only independent producers continue to explore for Leadville oil targets in the region, 85 percent of which is under the stewardship of the federal government. This environmentally sensitive, 7500-square-mile (19,400 km^2) area is relatively unexplored with only about 100 exploratory wells that penetrated the Leadville (less than one well per township), and thus the potential for new discoveries remains great.

The overall goals of this study are to (1) develop and demonstrate techniques and exploration methods never tried on the Leadville Limestone, (2) target areas for exploration, (3) increase deliverability from new and old Leadville fields through detailed reservoir characterization, (4) reduce exploration costs and risk especially in environmentally sensitive areas, and (5) add new oil discoveries and reserves.

The Utah Geological Survey (UGS) and Eby Petrography & Consulting, Inc., have entered into a cooperative agreement with the U.S. Department of Energy (DOE) as part of its Advanced and Key Oilfield Technologies for Independents (Area 2 – Exploration) Program. The project is being conducted in two phases, each with specific objectives and separated by a continue-stop decision point based on results as of the end of Phase I (Budget Period I). The objective of Phase I was to conduct a case study of the Leadville reservoir at Lisbon field (the largest Leadville oil producer in the Paradox Basin), San Juan County, Utah, in order to understand the reservoir characteristics and facies that can be applied regionally. Phase I has been completed and Phase II (Budget Period II) approved by DOE. The first objective of Phase II will be to conduct a low-cost field demonstration of new exploration technologies to identify potential Leadville oil migration directions (evaluating the middle Paleozoic hydrodynamic pressure regime), and surface geochemical anomalies, especially in environmentally sensitive areas. The second objective will be to determine regional facies (evaluating cores, geophysical well logs, outcrop and modern analogs), identify potential oil-prone areas based on shows (using low-cost epifluorescence techniques), and target areas for Leadville exploration.

These objectives are designed to assist the independent producers and explorers who have limited financial and personnel resources. All project maps, studies, and results will be publicly available in digital (interactive, menu-driven products on compact disc) or hard-copy format and presented to the petroleum industry through a proven technology transfer plan. The technology transfer plan includes a Technical Advisory Board composed of industry representatives operating in the Paradox Basin and a Stake Holders Board composed of representatives of state and federal government agencies, and groups with a financial interest within the study area. Project results will also be disseminated via the UGS Web site, technical workshops and seminars, field trips, technical presentations at national and regional professional meetings, convention displays, and papers in various technical or trade journals, and UGS publications.

This report covers research and technology transfer activities for the first half of the third project year (October 1, 2005, through March 31, 2006), Budget Period II. This work consisted of (1) describing Paleozoic brine chemistry and regional brine chemistry trends in the Paradox Basin, and (2) conducting a surface geochemical survey over the Lisbon case-study field area, Utah.

Project Benefits and Potential Application

Exploring for the Leadville Limestone is high risk, with less than a 10 percent chance of success based on the drilling history of the region. Prospect definition requires expensive, three-dimensional (3D) seismic acquisition, often in environmentally sensitive areas. These facts make exploring difficult for independents that have limited funds available to try new, unproven techniques that might increase the chance of successfully discovering oil. We believe that one or more of the project activities will reduce the risk taken by an independent producer in looking for Leadville oil, not only in exploring but in trying new techniques. For example, the independent would not likely attempt surface geochemical surveys without first knowing they have been proven successful in the region. If we can prove geochemical surveys are an effective technique in environmentally sensitive areas, the independent will save both time and money exploring for Leadville oil.

Another problem in exploring for oil in the Leadville Limestone is the lack of published or publicly available geologic and reservoir information, such as regional facies maps, complete reservoir characterization studies, surface geochemical surveys, regional hydrodynamic pressure regime maps, and oil show data and migration interpretations. Acquiring this information or producing these studies would save cash and manpower resources which independents simply do not possess or normally have available only for drilling. The technology, maps, and studies generated from this project will help independents to identify or eliminate areas and exploration targets prior to spending significant financial resources on seismic data acquisition and environmental litigation, and therefore increase the chance of successfully finding new accumulations of Leadville oil.

These benefits may also apply to other high-risk, sparsely drilled basins or regions where there are potential shallow-marine carbonate reservoirs equivalent to the Mississippian Leadville Limestone. These areas include the Utah-Wyoming-Montana thrust belt (Madison Limestone), the Kaiparowits Basin in southern Utah (Redwall Limestone), the Basin and Range Province of Nevada and western Utah (various Mississippian and other Paleozoic units), and the Eagle Basin of Colorado (various Mississippian and other Paleozoic units).

Many mature basins have productive carbonate reservoirs of shallow-marine shelf origin. These mature basins include the Eastern Shelf of the Midland Basin, West Texas (Pennsylvanian-age reservoirs in the Strawn, Canyon, and Cisco Formations); the Permian Basin, West Texas and southeast New Mexico (Permian age Abo and other formations along the northwest shelf of the Permian Basin); and the Illinois Basin (various Silurian units). A successful demonstration in the Paradox Basin makes it very likely that the same techniques could be applied in other basins as well. In general, the average field size in these other mature basins is larger than fields in the Paradox Basin. Even though there are differences in depositional facies and structural styles between the Paradox Basin and other basins, the fundamental use of the techniques and methods is a critical commonality.

PARADOX BASIN - OVERVIEW

The Paradox Basin is located mainly in southeastern Utah and southwestern Colorado, with a small portion in northeastern Arizona and northwestern New Mexico (figure 1). The Paradox Basin is an elongate, northwest-southeast-trending, evaporitic basin that predominately developed during the Pennsylvanian. The basin can generally be divided into three areas: the Paradox fold and fault belt in the north, the Blanding sub-basin in the south-southwest, and the Aneth platform in southeasternmost Utah (figure 1). The Mississippian Leadville Limestone is one of two, major oil and gas reservoirs in the Paradox Basin, the other being the Pennsylvanian Paradox Formation (figure 2); minor amounts of oil are produced from the Devonian McCracken Sandstone at Lisbon field. Most Leadville production is from the Paradox fold and fault belt (figure 3).

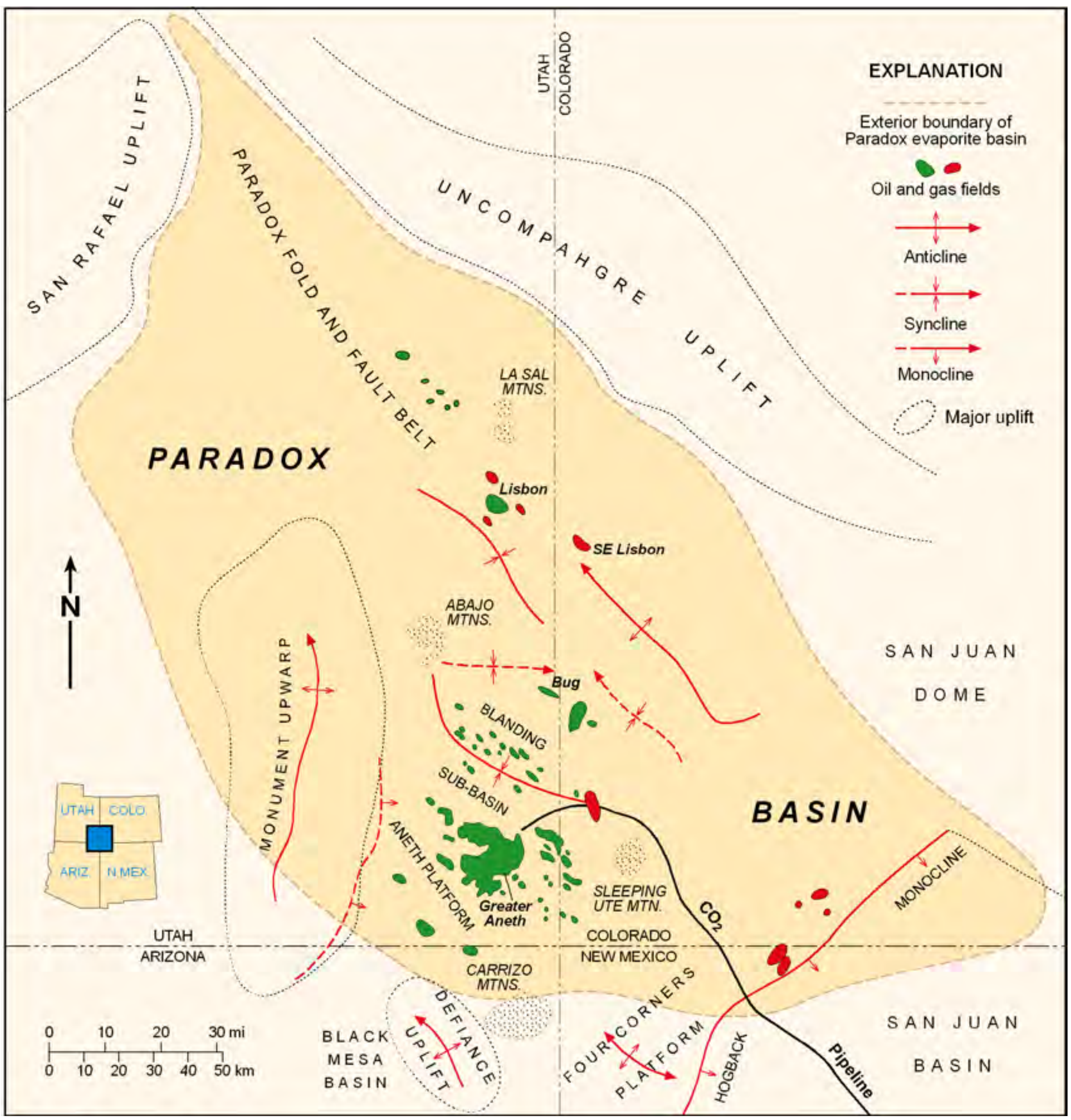


Figure 1. Oil and gas fields in the Paradox Basin of Utah and Colorado.

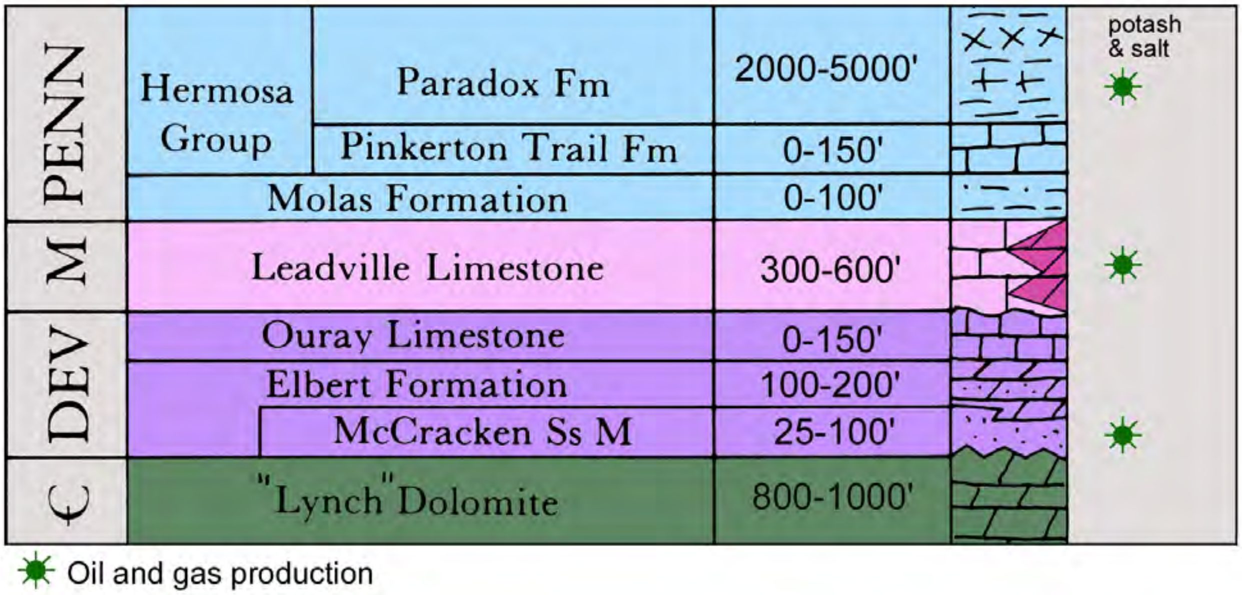


Figure 2. Stratigraphic column of a portion of the Paleozoic section determined from subsurface well data in the Paradox fold and fault belt, Grand and San Juan Counties, Utah (modified from Hintze, 1993).

The most obvious structural features in the basin are the spectacular anticlines that extend for miles in the northwesterly trending fold and fault belt. The events that caused these and many other structural features to form began in the Proterozoic, when movement initiated on high-angle basement faults and fractures 1700 to 1600 Ma (Stevenson and Baars, 1987). During Cambrian through Mississippian time, this region, as well as most of eastern Utah, was the site of typical, thin, marine deposition on the craton while thick deposits accumulated in the miogeocline to the west (Hintze, 1993). However, major changes occurred beginning in the Pennsylvanian. A series of basins and fault-bounded uplifts developed from Utah to Oklahoma as a result of the collision of South America, Africa, and southeastern North America (Kluth and Coney, 1981; Kluth, 1986), or from a smaller scale collision of a microcontinent with south-central North America (Harry and Mickus, 1998). One result of this tectonic event was the uplift of the Ancestral Rockies in the western United States. The Uncompahgre Highlands in eastern Utah and western Colorado initially formed as the westernmost range of the Ancestral Rockies during this ancient mountain-building period. The southwestern flank of the Uncompahgre Highlands (uplift) is bounded by a large, basement-involved, high-angle, reverse fault identified from seismic surveys and exploration drilling. As the highlands rose, an accompanying depression, or foreland basin, formed to the southwest – the Paradox Basin. Rapid subsidence, particularly during the Pennsylvanian and continuing into the Permian, accommodated large volumes of evaporitic and marine sediments that intertongue with non-marine arkosic material shed from the highland area to the northeast (Hintze, 1993).

The Paradox Basin is surrounded by other uplifts and basins, which formed during the Late Cretaceous-early Tertiary Laramide orogeny (figure 1). The Paradox fold and fault belt was created during the Tertiary and Quaternary by a combination of (1) reactivation of basement normal faults, (2) salt flowage, dissolution, and collapse, and (3) regional uplift (Doelling, 2000).

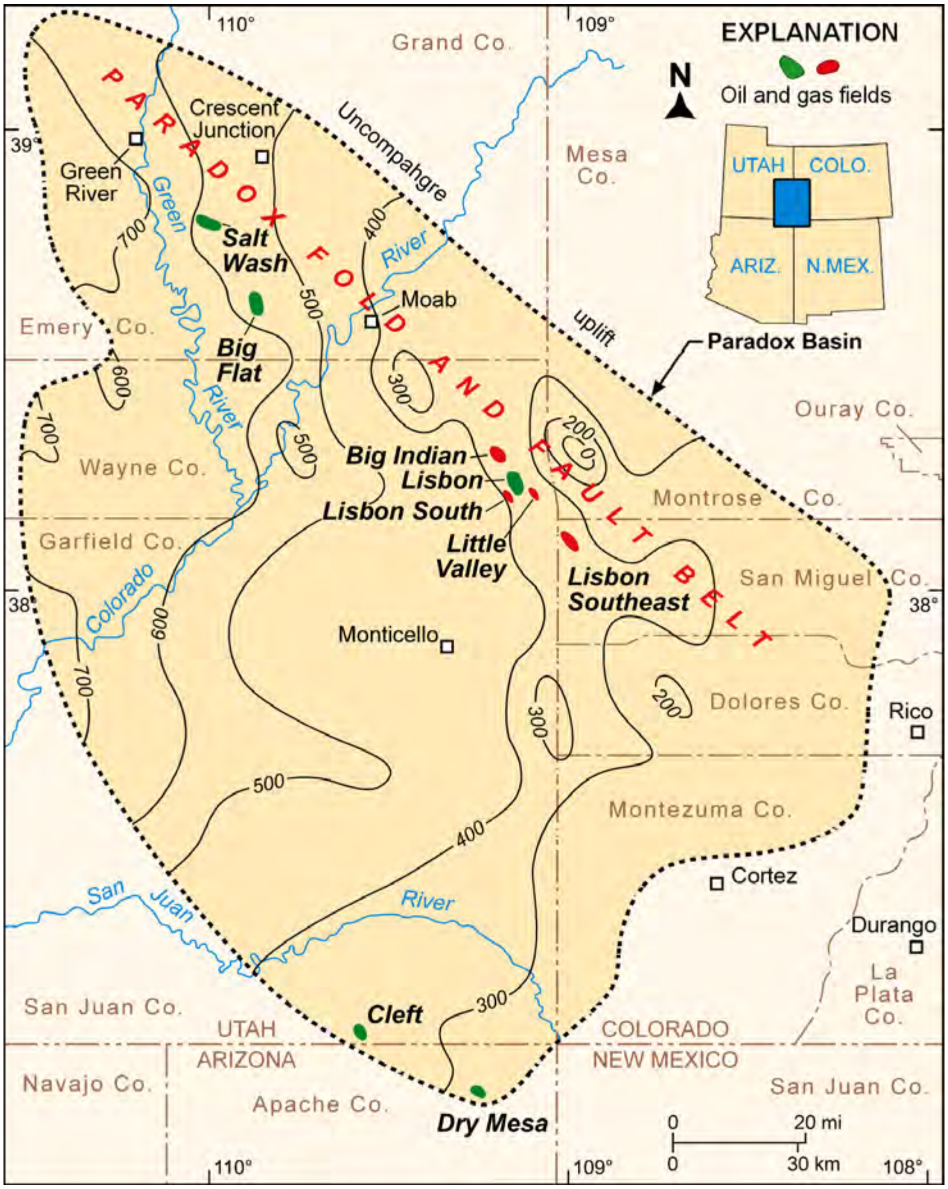


Figure 3. Location of fields that produce from the Mississippian Leadville Limestone, Utah and Colorado. Thickness of the Leadville is shown; contour interval is 100 feet (modified from Parker and Roberts, 1963).

Most oil and gas produced from the Leadville Limestone is found in basement-involved, northwest-trending structural traps with closure on both anticlines and faults (figure 4). Lisbon, Big Indian, Little Valley, and Lisbon Southeast fields (figure 3) are sharply folded anticlines that close against the Lisbon fault zone. Salt Wash and Big Flat fields (figure 3), northwest of the Lisbon area, are unfaulted, east-west- and north-south-trending anticlines, respectively.

Outcrops ranging in age from Pennsylvanian through Cretaceous, with surficial Quaternary deposits, are found within the Paradox Basin, as illustrated in figure 5. The Appendix contains three stratigraphic sections representing the following areas: (1) the Moab-

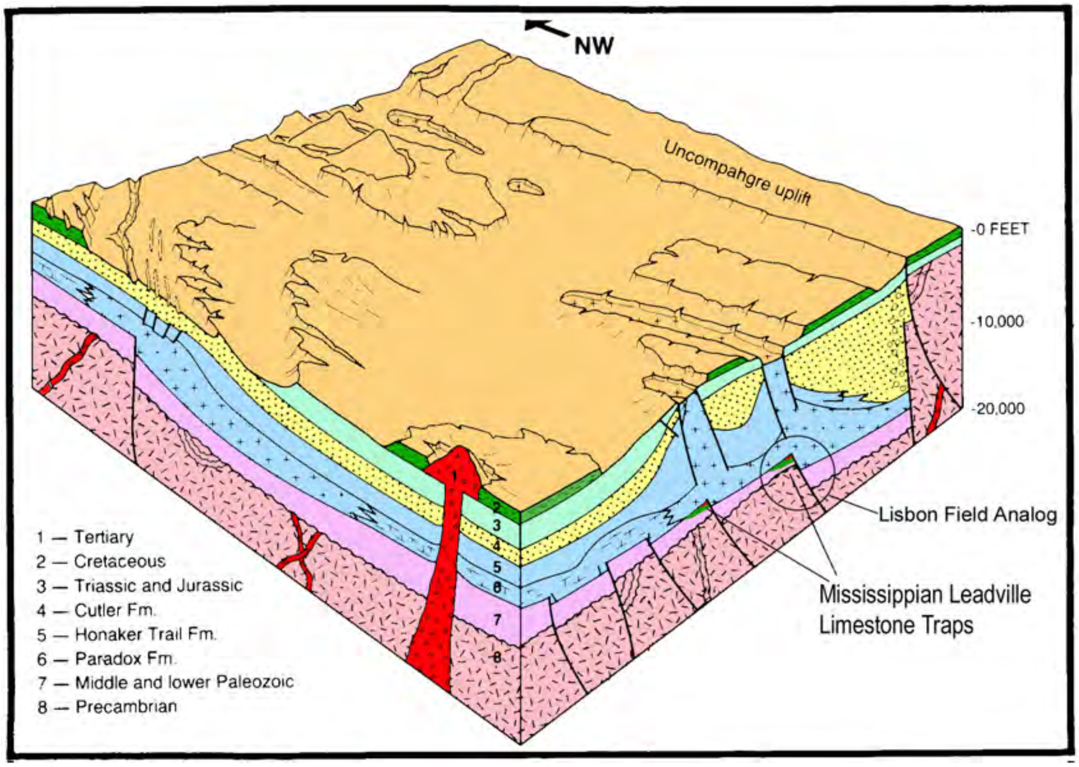


Figure 4. Schematic block diagram of the Paradox Basin displaying basement-involved structural trapping mechanisms for the Leadville Limestone fields (modified from Petroleum Information, 1984; original drawing by J.A. Fallin).

Arches-La Sal area, (2) the Canyonlands Park area, and (3) the Monticello-Bluff-Aneth area. In the Moab-Arches-La Sal area, the Jurassic Navajo Sandstone is exposed at the surface; in the Canyonlands Park area, the Cedar Mesa Sandstone is exposed at the surface; and in the Monticello-Bluff-Aneth area, the Dakota Sandstone/Burro Canyon Formation units are exposed at the surface.

MISSISSIPPIAN/ DEVONIAN AND PENNSYLVANIAN BRINE CHEMISTRY AND TRENDS WITHIN THE PARADOX BASIN, UTAH – RESULTS AND DISCUSSION

Introduction

The focus of this section is the chemistry and changes in chemistry of the brines found in the Mississippian/Devonian and Pennsylvanian formations in the Paradox Basin. From analyses of this information inferences can be made as to the migration history, and possible pathways and direction of hydrocarbons in the Leadville Limestone.

Chemical data for Mississippian/Devonian and Pennsylvanian oil-well brines from the Paradox Basin were obtained from published literature, Utah Division of Oil, Gas and Mining files, oil companies, and various other sources (Breit, no date; Gwynn, 1995). These data

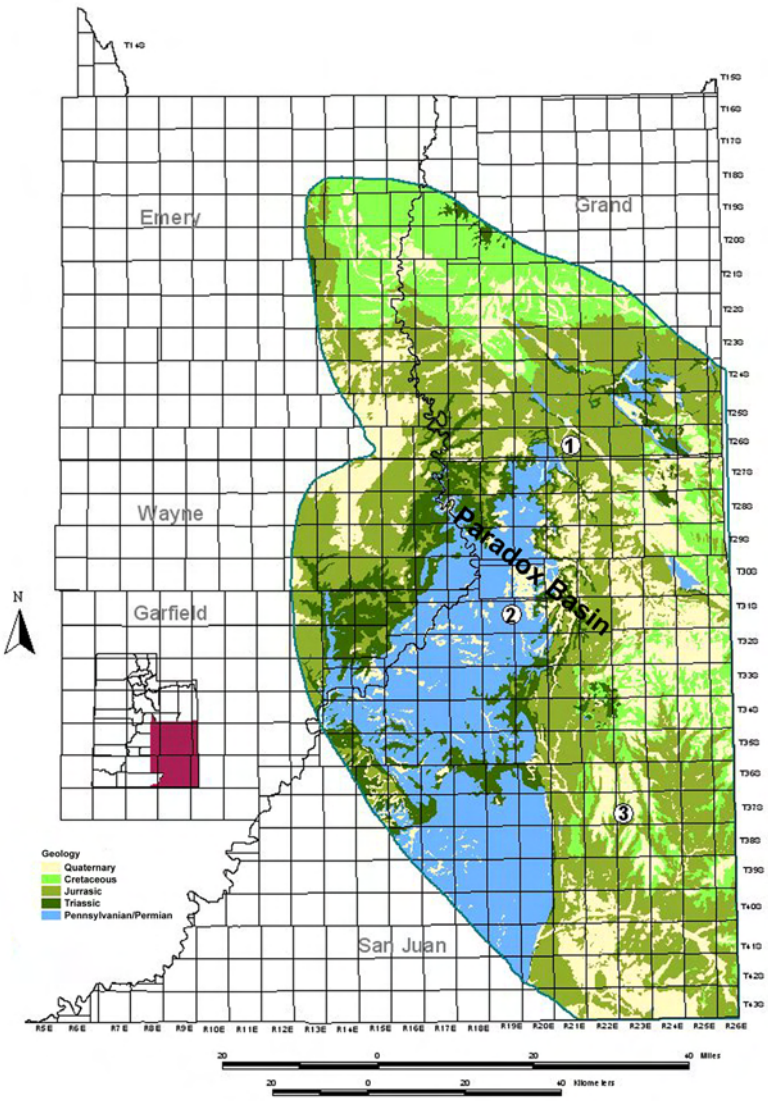


Figure 5. General geology of the Paradox Basin, and the locations (1 through 3) of the stratigraphic sections shown in Appendix.

include analyses from production, drillstem, swab, and other types of well tests. Considerable effort was expended to ensure that the analyses from Gwynn (1995) were within a mole imbalance of less than 5 percent. The mole imbalances of the samples from Breit (no date) were not determined. Data are displayed as (1) histograms to show the elevation intervals of the samples, (2) Piper and Stiff diagrams to show the distribution of the major cations and anions, and (3) scatter plots overlain by best-fit lines to show the north-to-south variations of these ions within the Paradox Basin.

Previous studies on the brine chemistry of the Paradox Basin include those of Hanshaw and Hill (1969), Huntoon (1979), Howells (1990) and Spangler and others (1996). Howells (1990) provides detailed information on the stratigraphy within San Juan County, including the maximum reported strata thickness, lithology, and hydrologic characteristics and significance of the various formations. Spangler and others (1996) provide information on the hydrology, chemical quality, and salinity in the Jurassic Navajo Sandstone aquifer in the Greater Aneth field area (figure 1).

Mississippian – Devonian Brines

The distribution of Mississippian-Devonian sample locations is shown in figure 6. The majority of the samples are located in the northern portion of the Paradox Basin within Grand, Emery, Wayne, and San Juan Counties. A smaller number of samples are found in the southern portion of the Paradox Basin (the southeast corner of San Juan County) in the Greater Aneth field area. The elevation of the "top of the sampled interval" for the majority of the samples lies between the -4000 (subsea) to 2000-foot (-1200-600 m) elevation interval, as shown in figure 7. This appears to be a much broader elevation range than for the Pennsylvanian samples, but the sampled intervals for the northern and southern areas are probably much different.

The distribution of the chemical composition of the Mississippian/Devonian brine samples is shown in the Piper and Stiff diagrams for the Mississippian, Devonian, and combined Mississippian and Devonian samples (figures 8 and 9). The cation components of the brines are predominantly sodium (Na) with minor amounts of calcium (Ca) and magnesium (Mg). The anion components in the brine are dominantly chloride (Cl) with a small number of brine samples having relatively high concentrations of sulfate (SO_4). Bicarbonate (HCO_3) is

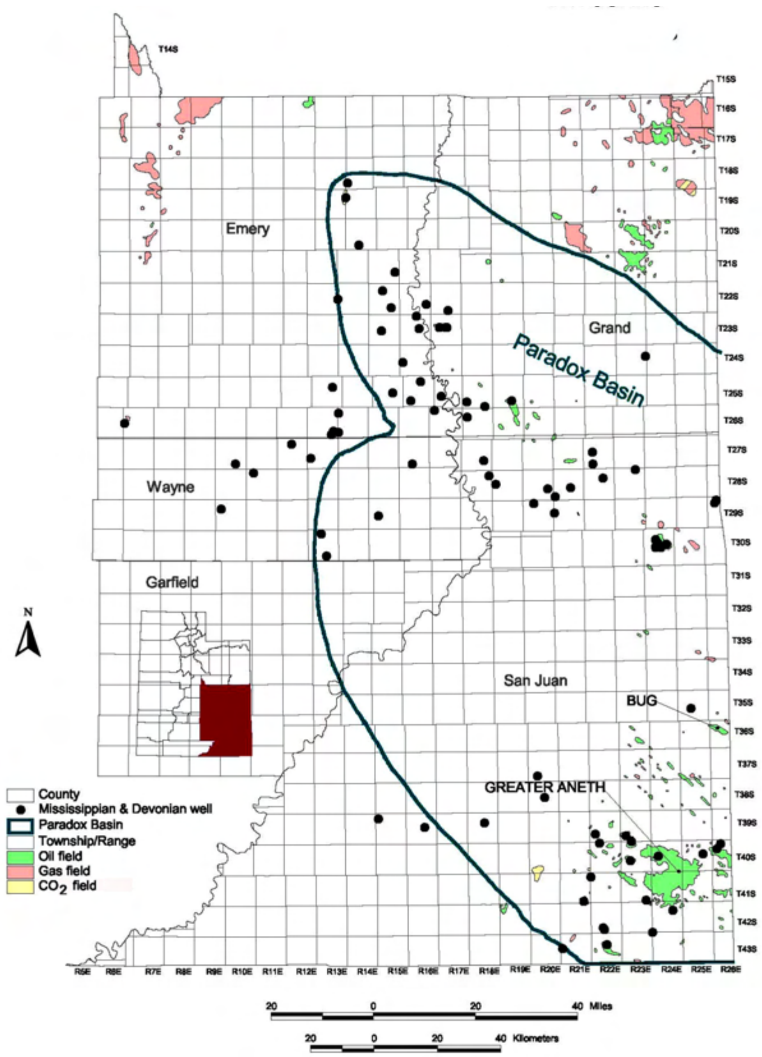


Figure 6. Locations of Mississippian/Devonian samples (wells), and oil and gas fields in the Paradox Basin and vicinity, Utah.

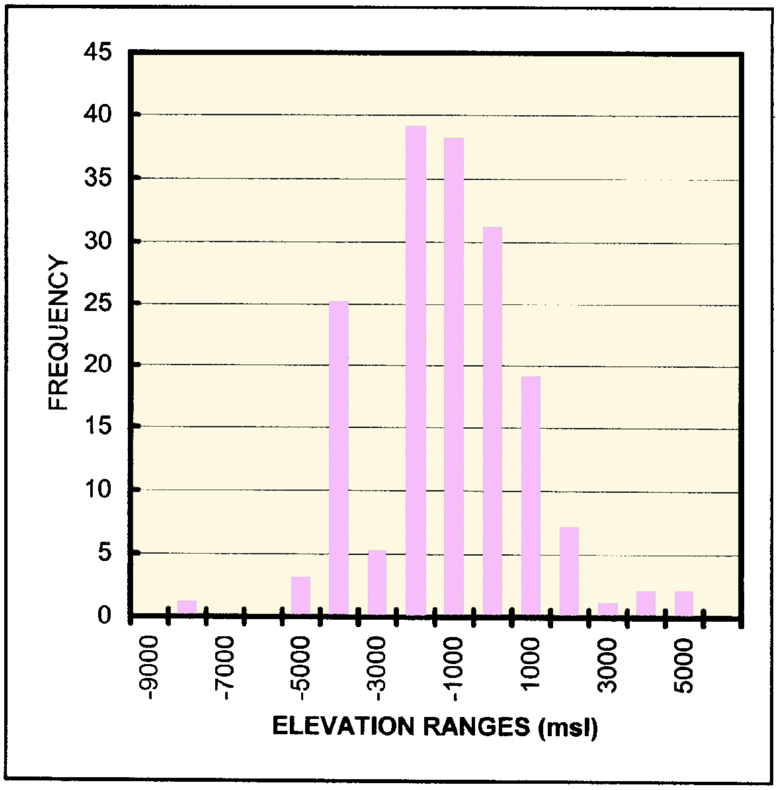


Figure 7. Elevation of the top of the sampled interval for the Mississippian/Devonian brine samples.

uniformly very low in these brines. Brines departing from the general trends are found mainly in San Juan and Wayne Counties.

Scatter plots (figures 10 and 11) show the elevation of the top of the sample interval, the chemistry of the samples (as individual ions), and total dissolved solids (TDS) versus their UTM-northing positions (from 4325000 on the north to 4075000 on the south). Fifth-degree polynomial best-fit lines indicate data trends from north (left) to south (right) through the length of the Paradox Basin.

Pennsylvanian Brines

The distribution of the wells from which the Pennsylvanian brine samples were collected is shown in figure 12. The majority of the samples are located in the southern portion of the Paradox Basin (the southeast corner of San Juan County), in and around the Greater Aneth and Bug fields (figure 1). A few scattered samples are also within or near the central and northern portions of the basin. The top of the sampled interval for the majority of the samples lies at about zero to 1000 feet (0-300 m) above mean sea level as shown in figure 13.

The distribution of the chemical composition of the Pennsylvanian brine samples is shown on Piper and Stiff diagrams (figures 14 and 15). The cations in most brine samples are Na-rich with a few samples containing greater percentages of Ca and to a lesser extent Mg. The anion components in the brine are Cl dominated with a smaller number of samples containing relatively high concentrations of SO_4. Bicarbonate is very low in these brines. Brines departing from the general trends are found mainly in San Juan and Wayne Counties. The high salinity of Pennsylvanian brines is probably due to their association with the bedded salts in the Paradox Formation.

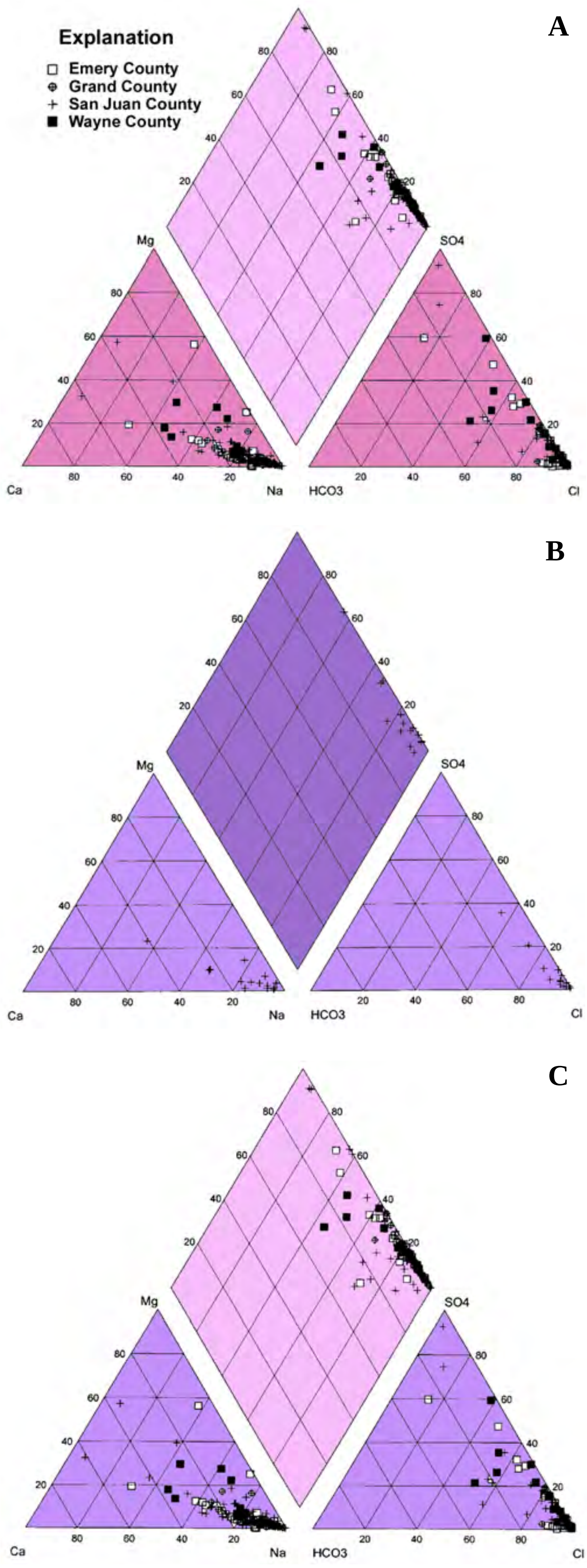


Figure 8. Piper diagrams showing the composition of (A) Mississippian brines, (B) Devonian brines, and (C) Mississippian and Devonian brines combined, in the Paradox Basin and vicinity, Utah.

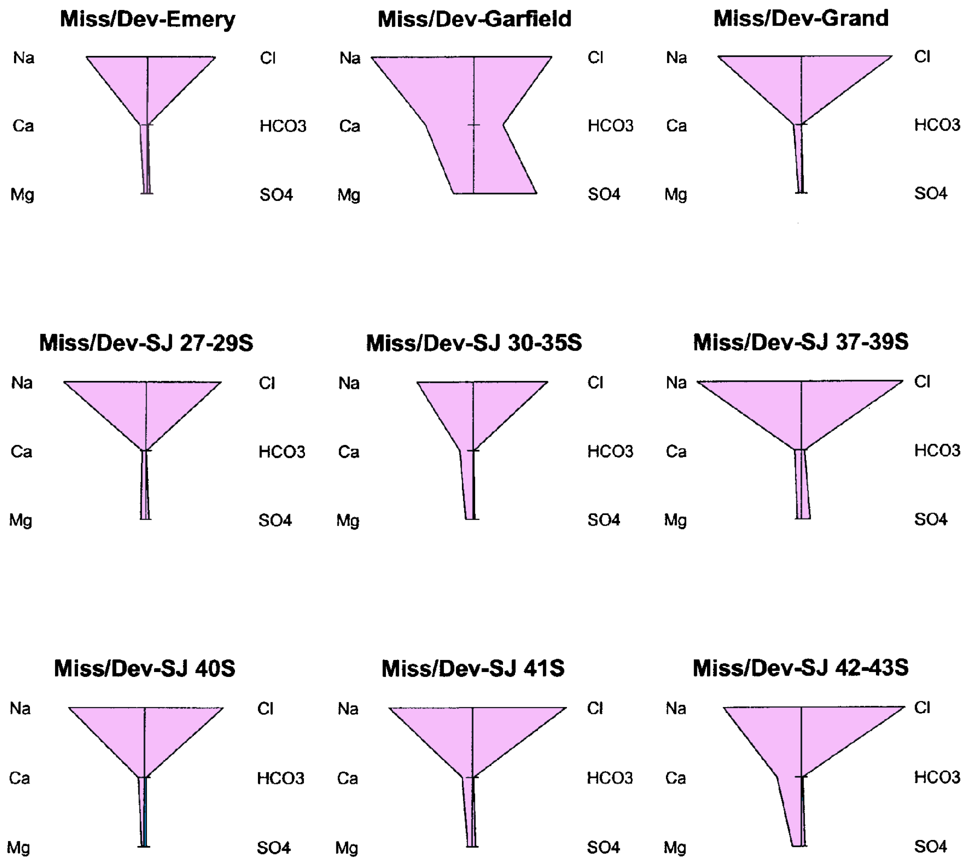


Figure 9. Stiff diagrams for Mississippian and Devonian (Miss/Dev) brines combined, by county (SJ = San Juan County) and township interval within the range indicated above the diagram.

Based on scatter plots (figures 16 and 17), the few Pennsylvanian samples present in the northern portion of the Paradox Basin suggest lower concentrations of Na, Mg, Ca, Cl, TDS, and higher SO_4 as compared to the Bug and Greater Aneth field areas. The elevation of the top of the sampled interval is somewhat lower than it is in the vicinity of Bug field, but higher than in the Greater Aneth field area.

Sodium, Mg, Ca, Cl, and TDS concentrations approach a maximum value in the area of Bug field, and then show decreasing concentration southward through the Greater Aneth field area. Bicarbonate and SO_4 concentrations both reach minimum values between Bug field and the Greater Aneth field area, but then rise southward toward T. 43 S., Salt Lake Base Line and Meridian (SLBL&M).

Direction of Brine Movement

Hanshaw and Hill (1969) provide a detailed discussion of the geochemistry and hydrodynamics of the Paradox Basin region, and include potentiometric maps of the Mississippian Leadville Limestone; the Pennsylvanian Pinkerton Trail, Paradox, and Honaker Trail Formations of the Hermosa Group; and the Permian formations. In their discussion, they summarize the areas of recharge and movement of ground water as follows:

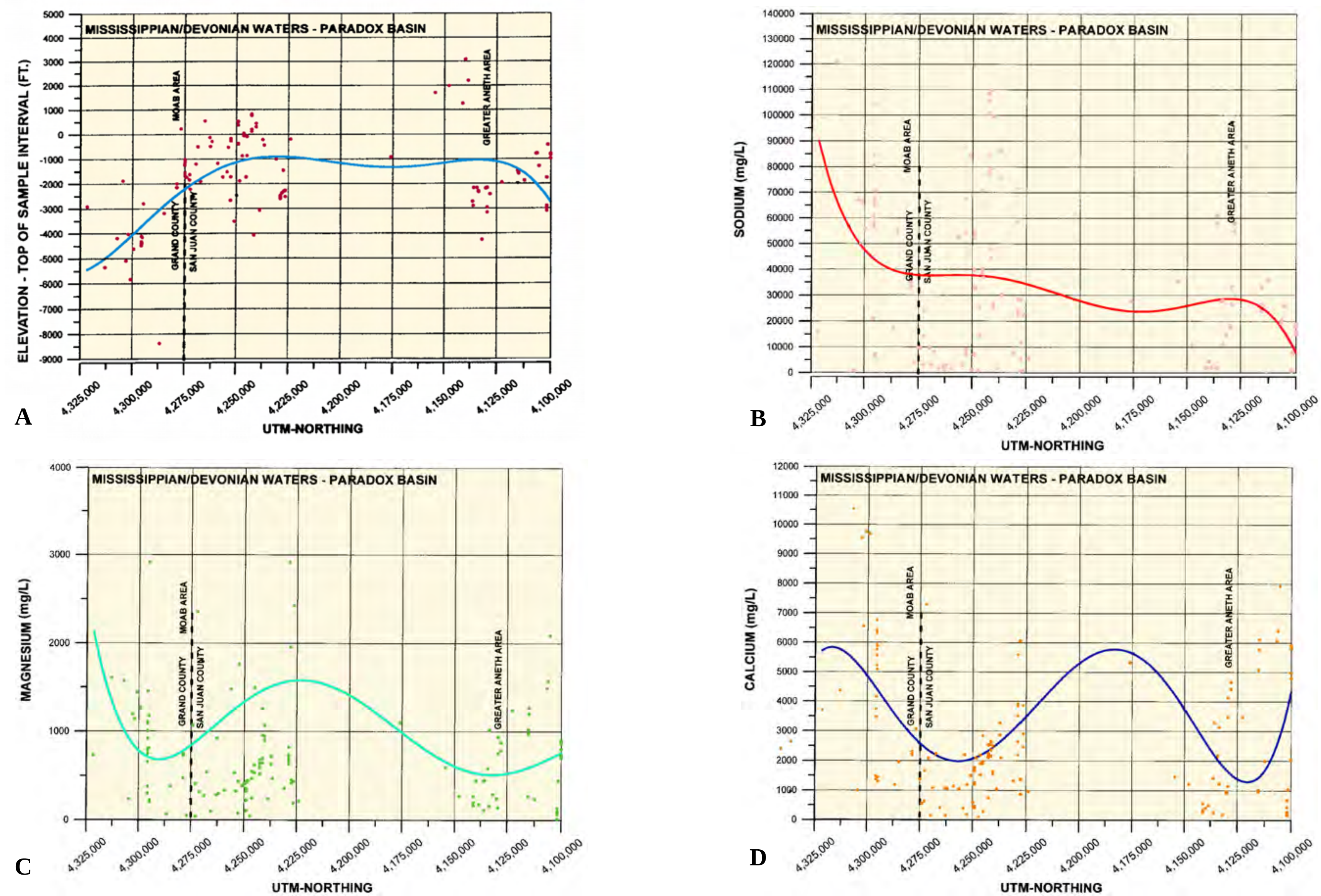


Figure 10. Scatter plots showing the elevation of the top of the sample interval (A), and sodium (B), magnesium (C), and calcium (D) contents versus geographic location (UTM-northing) for the Mississippian/Devonian samples. Fifth-degree polynomial best-fit lines indicate data trends from north (left) to south (right) through the length of the Paradox Basin. The general areas of the Greater Aneth and Bug fields are shown, as well as the Grand-San Juan County line.

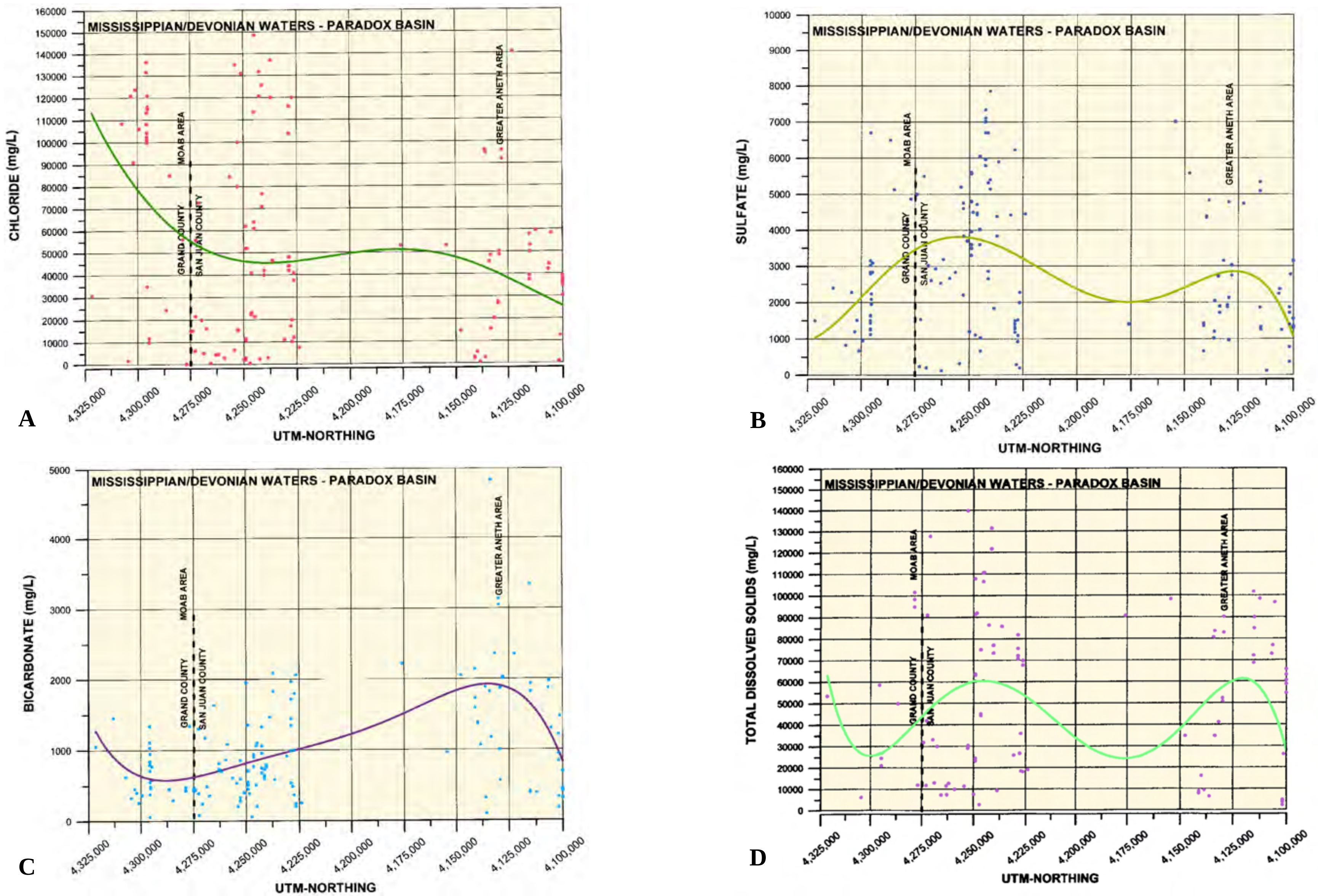


Figure 11. Scatter plots of chloride (A), sulfate (B), bicarbonate (C), and total dissolved solids (D) versus geographic location (UTM-northing) for the Mississippian/Devonian samples. Fifth-degree polynomial best-fit lines indicate data trends from north (left) to south (right) through the length of the Paradox Basin. The general areas of the Greater Aneth and Bug fields are shown, as well as the Grand-San Juan County line.

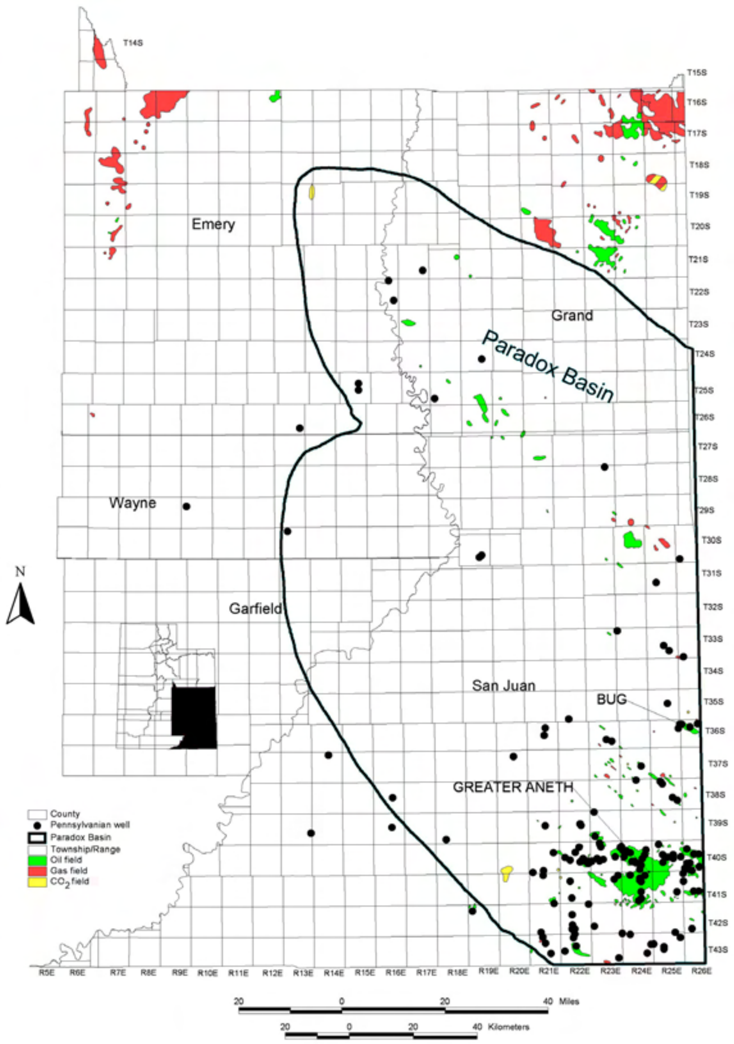


Figure 12. Locations of Pennsylvanian brine samples (wells), and oil and gas fields in the Paradox Basin and vicinity, Utah.

The principal areas of recharge to aquifers in the Paradox Basin are the west flank of the San Juan Mountains and the west flank of the Uncompahgre uplift. The direction of ground-water movement in each unit studied [Mississippian rocks, Pinkerton Trail Limestone, Paradox Member of the Hermosa Formation, Honaker Trail Formation, and the Permian formations] is principally southwestward toward the topographically low outcrop areas along the Colorado River in Arizona. However, at any point in the basin, flow may be in some other direction owing to the influence of intrabasin recharge areas or local obstructions to flow, such as faults or dikes. Many structurally and topographically high areas within the basin are above the regional potentiometric surface; recharge in these areas will drain rapidly off the highs and adjust to the regional water level.

Discussion

Table 1 gives averaged values for ground elevation, top and bottom elevation of the sampled interval, TDS, and ions for individual counties, and for township intervals within San Juan County. Based on the data in table 1, the following can be said:

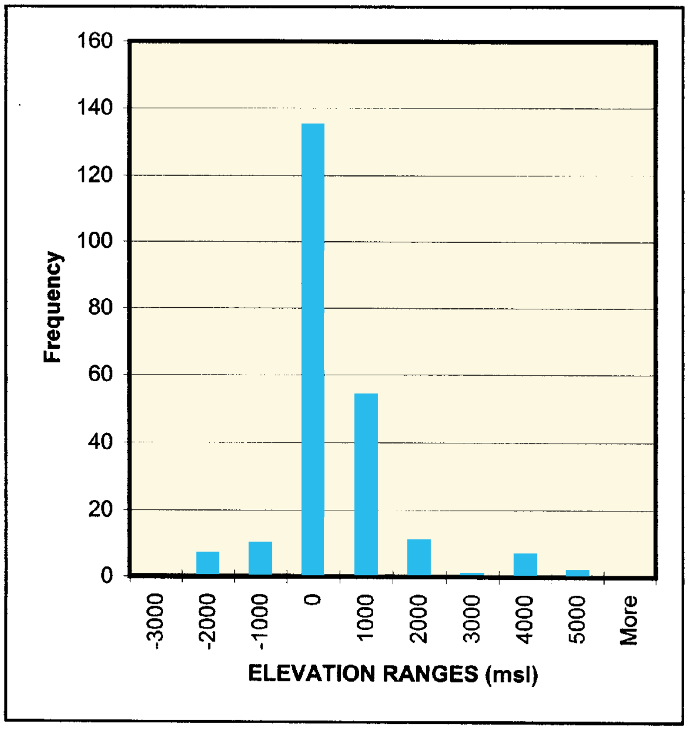


Figure 13. Elevation of the top of sampled interval for Pennsylvanian brine samples.

1. For Mississippian/Devonian brines, the samples from Grand County have the highest average TDS values, followed by San Juan, Emery, and Garfield. For Pennsylvanian brines, the samples from Grand County also have the highest average TDS of all the counties in the study area, followed by San Juan, Emery, and Wayne.

2. The Na, Mg, Ca, and Cl contents of the Pennsylvanian brines are consistently higher, in a given county or township interval (for instance T. 40 S., SLBL&M, in San Juan County), than the Mississippian/Devonian brines in the same interval, while the average values for SO_4 and HCO_3 are lower.

3. From the Piper and Stiff diagrams (figures 8A, 8B, 9, 14, and 15), it can be concluded that the brines in both the Mississippian/Devonian and Pennsylvanian systems are mainly NaCl in nature, with end-member samples whose cations contain about 70 percent Ca and 30 percent Mg, and whose anion makeup approaches a high-SO_4 brine. From the scatter plots (figures 10, 11, 16, and 17), it appears that these end-member brines are found to the south of the Greater Aneth field area.

A comparison of the various average chemistries in table 1 is difficult to visualize because of the varied salt concentrations of the samples. Table 2 gives these data on a dry-weight basis. Based on these data, the following conclusions can be drawn regarding the Mississippian/Devonian and Pennsylvanian brine chemistries in the various counties:

1. The Mississippian/Devonian brines from Grand, Emery, and San Juan Counties are very similar, even though the TDS concentration of the Grand County brines is considerably higher than either Emery or San Juan County. Garfield County brines, like the Wayne County brines, are totally dissimilar.

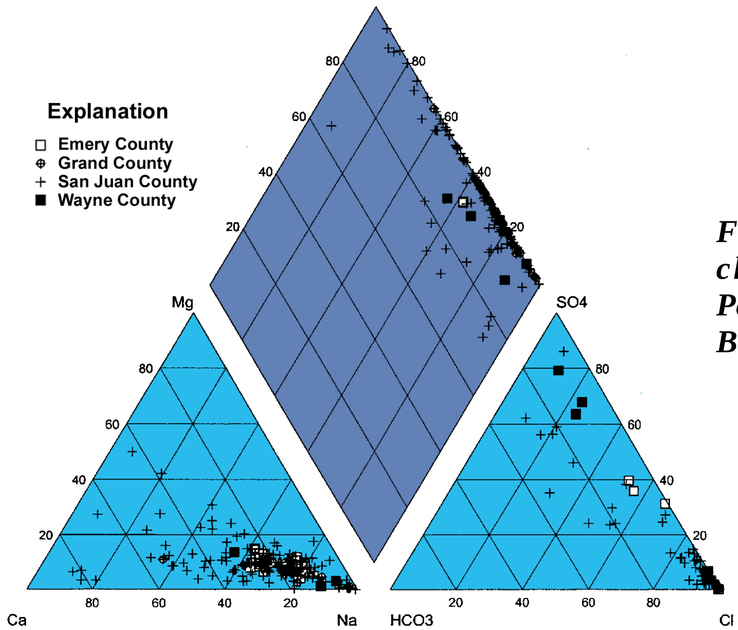


Figure 14. Piper diagram showing the chemical composition of the Pennsylvanian brines in the Paradox Basin by county.

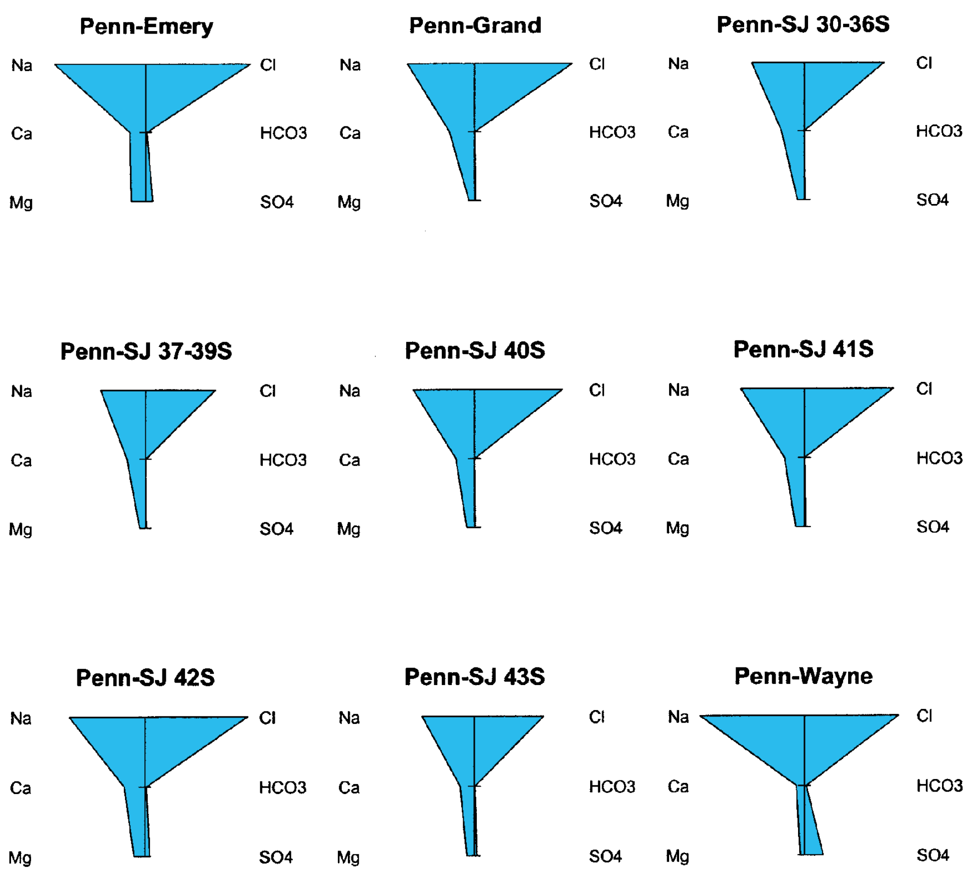


Figure 15. Stiff diagrams for Pennsylvanian (Penn) brines, by county (SJ = San Juan County) and township interval within the range indicated above the diagram.

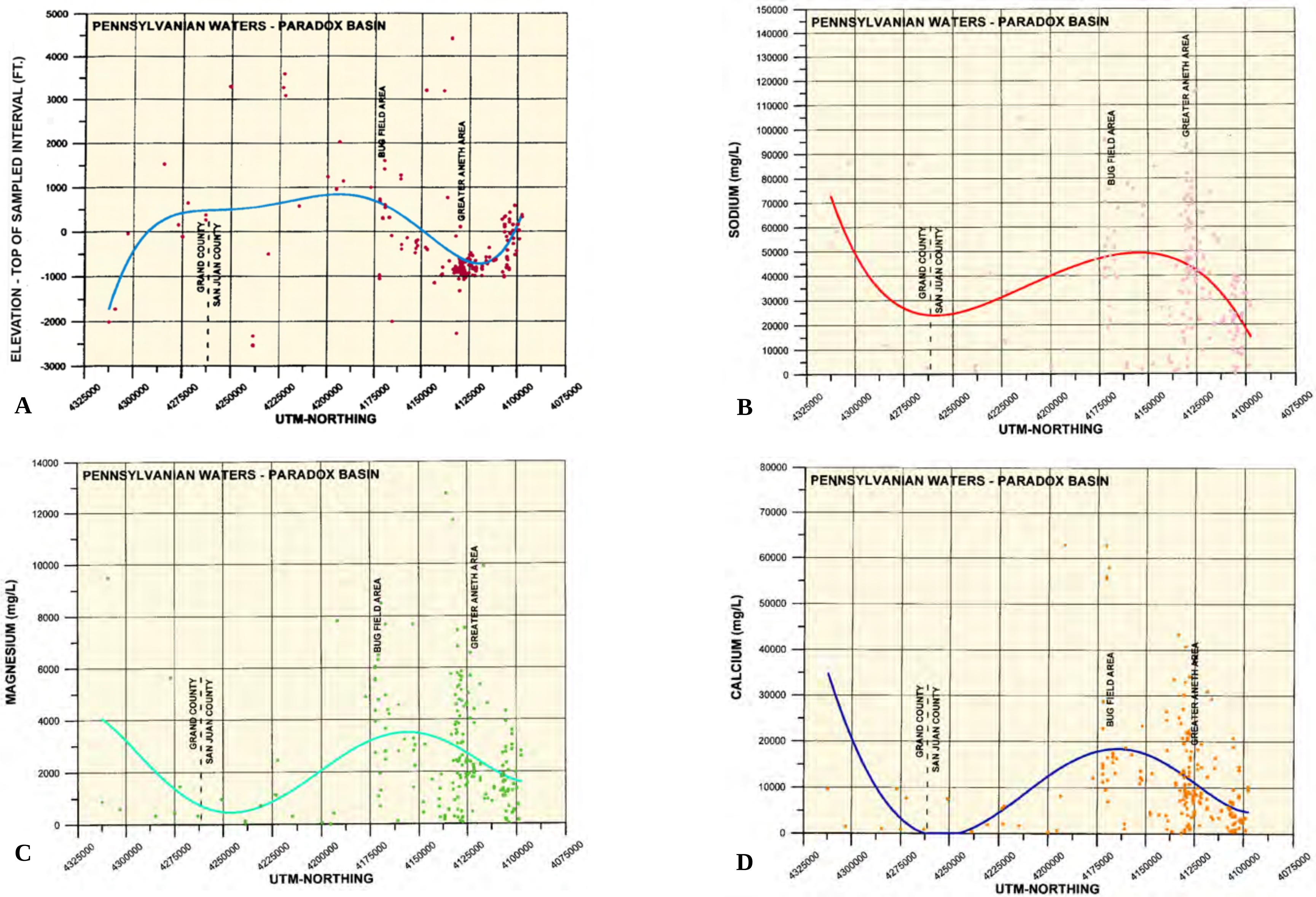


Figure 16. Scatter plots showing the elevation of the top of the sample interval (A), and sodium (B), magnesium (C), and calcium (D) contents versus geographic location (UTM-northing) for the Pennsylvanian samples. Fifth-degree polynomial best-fit lines indicate data trends from north (left) to south (right) through the length of the Paradox Basin. The general areas of the Greater Aneth and Bug fields are shown, as well as the Grand-San Juan County line.

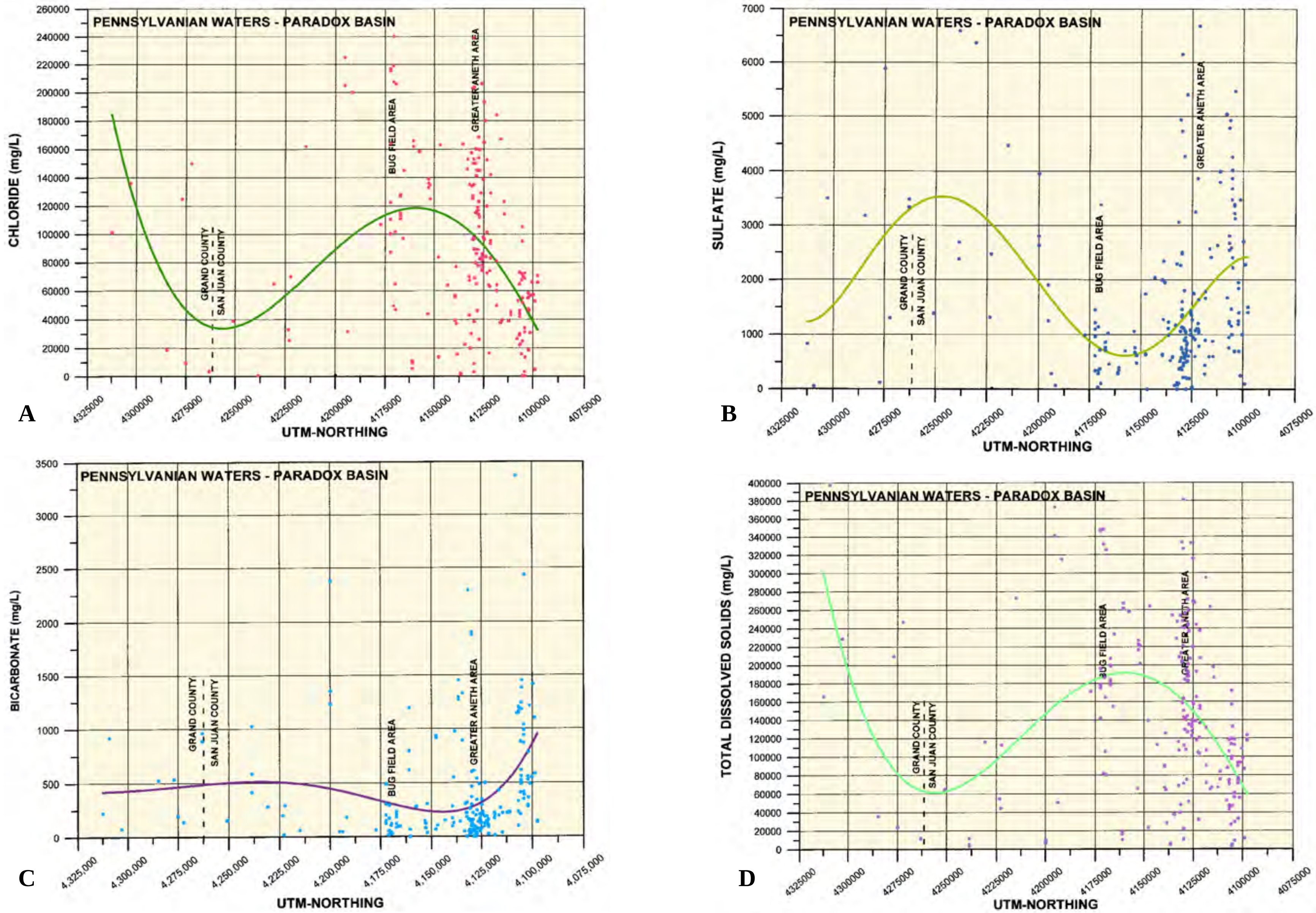


***Figure 17.** Scatter plots of chloride (A), sulfate (B), bicarbonate (C), and total dissolved solids (D) versus geographic location (UTM-northing) for the Pennsylvanian samples. Fifth-degree polynomial best-fit lines indicate data trends from north (left) to south (right) through the length of the Paradox Basin. The general areas of the Greater Aneth and Bug fields are shown, as well as the Grand-San Juan County line.*

Table 1. Brine sample location, averaged ground elevation, top and bottom elevation of the sampled interval, TDS, and ions for individual counties, and for township intervals within San Juan County.

COUNTY	AGE	TWP-INTERVAL	ELEV	TOP-ELEV	BOT-ELEV	TDS	Na	Mg	Ca	Cl	SO_4	HCO_3
Grand	Penn	Grand	4518	-321	-385	214249	59288	2550	19198	131066	1772	375
Emery	Penn	Emery	5160	172	92	64339	20317	1690	3084	35399	3206	645
Wayne	Penn	Wayne	4892	-1976	-2056	34699	11815	246	788	16763	4510	577
San Juan	Penn	SJ 30-36S	6319	953	1004	177196	45717	3102	17185	109702	1228	262
San Juan	Penn	SJ 37-39S	5226	503	434	115110	30044	2003	10679	71006	878	501
San Juan	Penn	SJ 40S	4781	-825	-888	190857	53925	3611	14187	117895	1050	189
San Juan	Penn	SJ 41S	4721	-800	-868	148979	41502	2997	11241	91442	1627	172
San Juan	Penn	SJ 42S	4987	-170	-314	71723	20231	1511	4775	41637	2675	894
San Juan	Penn	SJ 43S	5202	-199	-257	79159	22916	1692	5379	46398	2332	739
		SJ Average	5206	-90	-148	130504	35723	2486	10574	79680	1632	460
Emery	Miss/Dev	Emery	4852	-2116	-2250	81229	27407	741	2906	46963	2432	710
Garfield	Miss/Dev	Garfield	5936	-1268	-1322	7472	1595	164	650	1848	2018	1197
Grand	Miss/Dev	Grand	4561	-4089	-4116	156376	54959	876	4481	92829	2578	651
San Juan	Miss/Dev	SJ 27-29S	5630	-798	-893	141402	55153	1643	2191	77243	4546	719
San Juan	Miss/Dev	SJ 30-35S	6320	-2300	-2422	84321	24886	1651	5004	50137	1637	966
San Juan	Miss/Dev	SJ 37-39S	5617	1090	1001	52048	18284	349	997	27727	3266	1426
San Juan	Miss/Dev	SJ 40S	4608	-2594	-2718	95537	33750	474	2234	54115	2463	2501
San Juan	Miss/Dev	SJ 41S	4848	-1759	-1872	109684	36913	996	3742	63057	3269	1707
San Juan	Miss/Dev	SJ 42-43S	5070	-873	-946	66618	18705	1071	5033	38828	1869	1113
		SJ Average	5349	-1206	-1308	91602	31282	1031	3200	51851	2842	1405

TWP-interval = A single county name means the average of all samples within that county.
SJ = the average of all samples within San Juan County.
ELEV = Average ground elevation of all sampling sites.
TOP-ELEV, BOT-ELEV = Average elevations of the top and bottom of the sampled intervals TDS = Total dissolved solids, reported in mg/L.
Individual ion values are reported in mg/L.

Table 2. Total dissolved solids (mg/L) and ions on a dry-weight-percent basis for brines from the Paradox Basin, Utah, by county.

Field Mississippian/Devonian Brine

Area	TDS	Na	Mg	Ca	Cl	SO_4	HCO_3
Grand Co	156376	35	1	3	59	2	<1
Emery Co	81229	34	1	4	58	3	1
Garfield Co	7472	21	2	9	25	27	16
All of San Juan Co	91602	34	1	3	57	3	2

Pennsylvanian Brine

Area	TDS	Na	Mg	Ca	Cl	SO_4	HCO_3
Grand Co	214249	28	1	9	61	1	<1
Emery Co	64339	32	3	5	55	5	1
Wayne Co	34699	34	1	2	48	13	2
All of San Juan Co	130504	28	2	8	62	1	<1

2. The Pennsylvanian brines from Grand and San Juan Counties are very similar, even though the TDS concentration of the Grand County brines is considerably higher. The brines from Emery and Wayne Counties are not similar to the brines of the other two counties, and the brines from Wayne County are totally dissimilar.

SURFACE GEOCHEMICAL SURVEY IN THE LISBON CASE-STUDY FIELD AREA, SAN JUAN COUNTY, UTAH – RESULTS AND DISCUSSION

Introduction

Surface exploration methods, such as geochemical, magnetic, and remote sensing, have increasingly proven to significantly reduce petroleum exploration risks and finding costs. These methods, and numerous case histories, are summarized by Schumacher and LeSchack (2002). Surface geochemical surveys in the Michigan and Williston Basins helped identify areas of poorly drained or by-passed oil in pinnacle reef fields (Wood and others, 2001, 2002), which are comparable in many aspects to the depositional environment of the Leadville Limestone in the Paradox Basin. Surface geochemical methods detected hydrocarbon microseepage over Grant Canyon field, Nevada, and these methods are also being used to define potential faulted, carbonate reservoirs in western Utah (Seneshen and others, 2006). Surface geochemical surveys represent a fast, low-cost alternative to 3D seismic acquisition, especially in environmentally sensitive areas such as the Paradox Basin. Anomalies are relatively easy to identify and are conclusive.

Lisbon field, San Juan County, Utah (figures 1 and 3) accounts for most of the Leadville oil production in the Paradox Basin. A wealth of Lisbon core, petrographic, and other data is available to the UGS. The reservoir characteristics, particularly diagenetic overprinting and history, and Leadville facies can be applied regionally to other fields and exploration trends in the Paradox Basin. Therefore, we selected Lisbon as the major case-study field for the Leadville Limestone project. Lisbon field is also ideal for a surface geochemical survey. Besides active hydrocarbon production from beneath easily the accessible area, the surface geology is similar to the subsurface structure of the field (figures 18 and 19). A major northwest-southeast-trending anticline (tens of miles in length) along the Lisbon fault, displaces the Pennsylvanian Honaker Trail Formation against Cretaceous strata. The Leadville reservoir in Lisbon field is separated from upper Paleozoic and Mesozoic strata by cyclic evaporites in the Pennsylvanian Paradox Formation. These conditions are typical of what might be expected when exploring for similar drilling targets in the basin.

The UGS contracted with Direct Geochemical of Golden, Colorado, to train UGS staff to conduct the sampling program; sample analysis and interpretation are being conducted by Direct Geochemical. This low-cost (around $150 per sample) surface geochemical survey began at Lisbon field in March 2006.

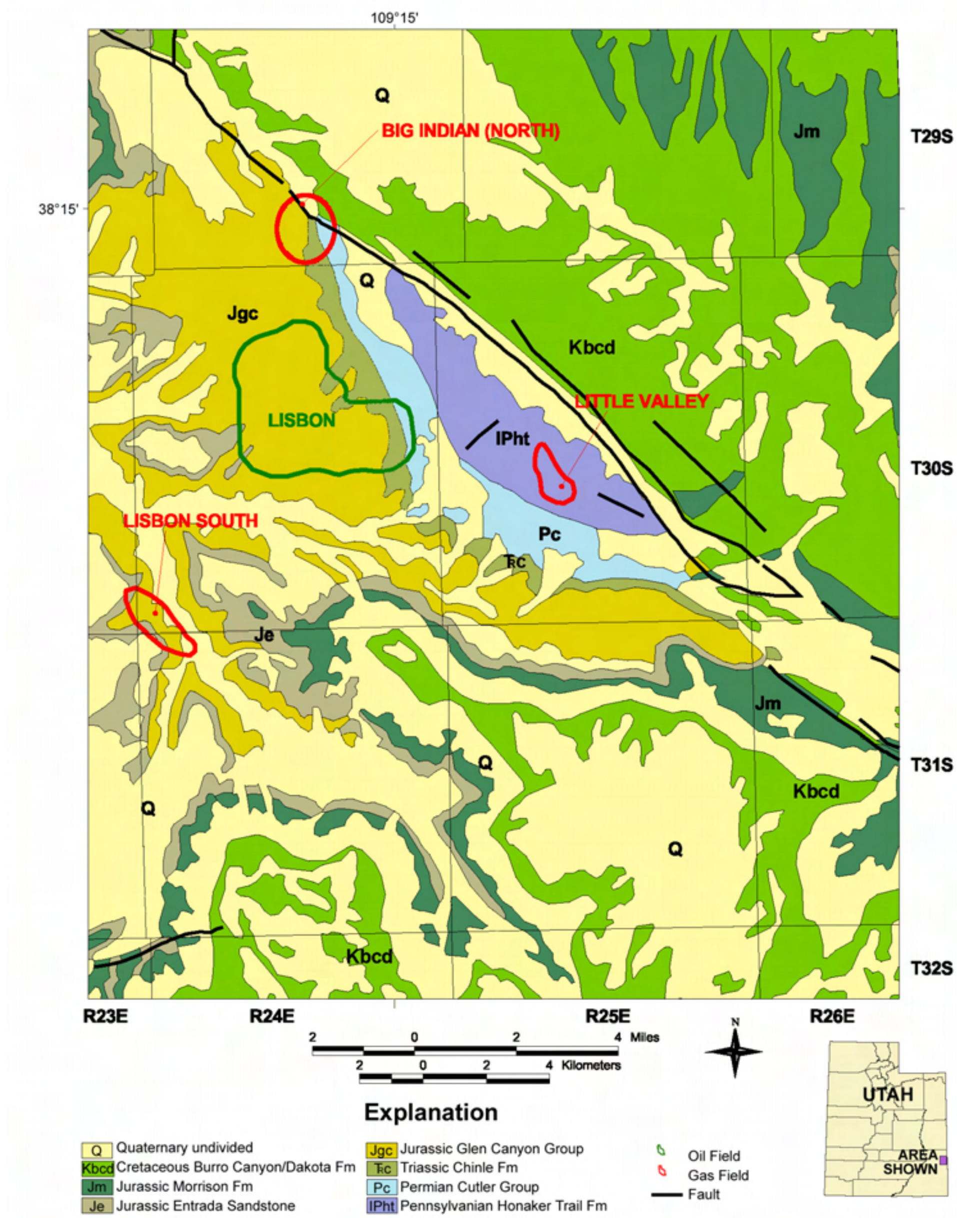


Figure 18. General surface geology of the Lisbon field area. Modified from Hintze and others (2000).

Field Synopsis

The Lisbon trap is an elongate, asymmetric, northwest-trending anticline, with nearly 2000 feet (600 m) of structural closure and bounded on the northeast flank by a major, basement-involved normal fault with over 2500 feet (760 m) of displacement (Smith and Prather, 1981) (figure 19). Several minor, northeast-trending normal faults divide the Lisbon Leadville reservoir into segments. This subsurface structure is similar to Lisbon South field, a 2004 Leadville Limestone discovery by ST Oil Company that occurs southwest of Lisbon field (figures 3 and 18).

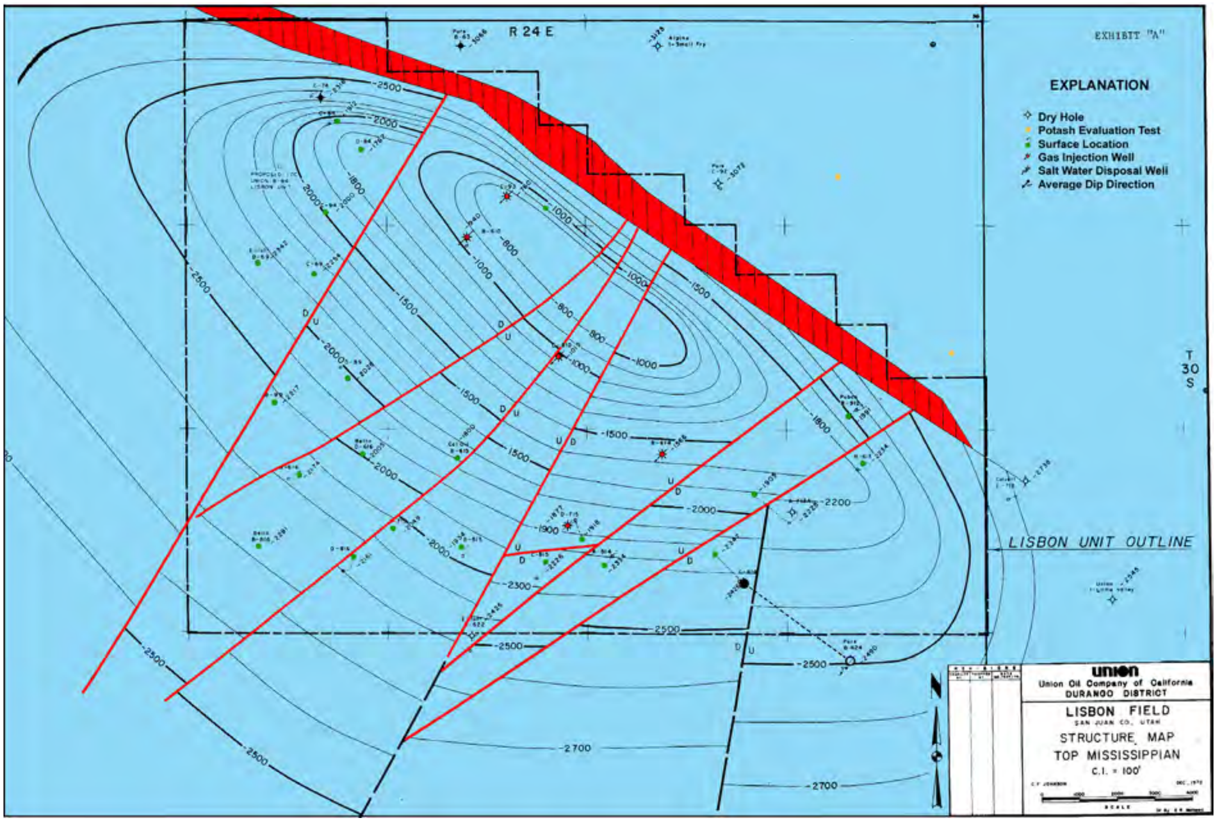


Figure 19.** **Top of structure of the Leadville Limestone, Lisbon field, San Juan County, Utah (modified from C.F. Johnson, Union Oil Company of California files, 1970; courtesy of Tom Brown, Inc.).

Producing units in Lisbon field contain dolomitized crinoidal/skeletal grainstone, packstone, and wackestone fabrics. Diagenesis includes fracturing, autobrecciation, karst development, hydrothermal dolomite, and bitumen plugging. The net reservoir thickness is 225 feet (69 m) over a 5120-acre (2100 ha) area (Clark, 1978; Smouse, 1993). Reservoir quality is greatly improved by natural fracture systems associated with the Paradox fold and fault belt. Porosity averages 6 percent in intercrystalline and moldic networks enhanced by fractures; permeability averages 22 millidarcies (mD). The drive mechanism is an expanding gas cap and gravity drainage; water saturation is 39 percent (Clark, 1978; Smouse, 1993). The bottom-hole temperature ranges from 153 to 189ºF (67-87ºC).

Lisbon field was discovered in 1960 with the completion of the Pure Oil Company No. 1 NW Lisbon USA well, NE1/4NW1/4 section 10, T. 30 S., R. 24 E., SLBL&M (figure 19), with an initial flowing potential of 179 bbls of oil per day (BOPD) (28 m^3) and 4376 thousand cubic feet of gas per day (124 MCMPD). The original reservoir field pressure was 2982 pounds per square inch (psi [20,560 kPa]) (Clark, 1978). There are currently 22 producing (or shut-in wells), 11 abandoned producers, five injection wells (four gas injection wells and one water/gas injection well), and four dry holes in the field. Cumulative production as of March 31, 2006, was 51,145,231 bbls of oil (8,132,092 m^3), 785.4 billion cubic feet of gas (BCFG) (22.2 BCMG) (cycled gas), and 50,073,622 bbls of water (7,961,706 m^3) (Utah Division of Oil, Gas and Mining, 2006). Gas that was re-injected into the crest of the structure to control pressure decline is now being produced.

Three factors create reservoir heterogeneity within productive zones: (1) variations in carbonate fabrics and facies, (2) diagenesis (including karstification), and (3) fracturing. The extent of these factors and how they are combined affect the degree to which they create barriers to fluid flow.

Previous Work

Remote sensing studies over Lisbon field have documented the presence of seep-induced alteration to near-surface soils and sediments (Segal and others, 1986; Merin and Segal, 1989; Segal and Merin, 1989). These studies used Landsat Thematic Mapper (TM) data to recognize the presence of kaolinite as well as reduced iron (bleached redbeds). A ratio of TM bands 2/3 was used to define variations in ferric-iron content, while a band 5/7 ratio was used to highlight variations in clay content. Because vegetation also exhibits high band 2/3 ratio values, it can be confused with bleached rocks. Vegetation also shows high band 5/7 ratio values, which can be confused with clay-rich rocks. A TM band 3/4 ratio was generated to define vegetated areas and reduce the chance for misclassification (Dietmar Schumacher, Geo-Microbial Technologies, written communication, August 3, 2005).

There have been no surface geochemical surveys and analysis published on the Lisbon field area.

Methods

Sample Collection

The geochemical survey consisted of collecting about 200 soil samples at 1500-foot (500 m) intervals on a 16-square-mile (42 km^2) rectangular grid over and around the Lisbon field to map the spatial distribution of surface hydrocarbon anomalies (figure 20). The sampling grid extends beyond the proven limits of Lisbon field to establish background readings. The area chosen sufficiently covers the oil-leg, gas cap, and background "barren" areas. In addition, samples were collected over oil, gas, and dry wells for analogue matching purposes and to refine the discriminant model for Lisbon field. Because these samples were collected only 3 feet (1 m) apart, they are essentially field duplicates, and can therefore be used to monitor within-site variation.

Shallow (generally 8- to 12-inch [20-30 cm] deep) soil samples were collected with a spade or tree-planting shovel over a 6-foot area (2 m) at each site. Care was taken to avoid sampling material sluffed off the surface. The soils were placed and stored in airtight, Teflon-sealed glass soil jars to prevent hydrocarbon contamination during transport to the laboratory in Golden, Colorado. Backup samples were also collected from each site and stored in plastic bags. Some sampling locations required adjustments due to a lack of soil (rock outcrop). Evidence of surface alteration that could be attributed to hydrocarbon seepage and fracturing was also noted. Sample sites around wells were located topographically high relative to the well pad to reduce the possibility of contamination.

Sample site location coordinates were recorded in the field notes and marked on a Global Positioning System (GPS). Prior to the survey, all sample site coordinates were generated in Garmin-compatible format for uploading to the GPS.

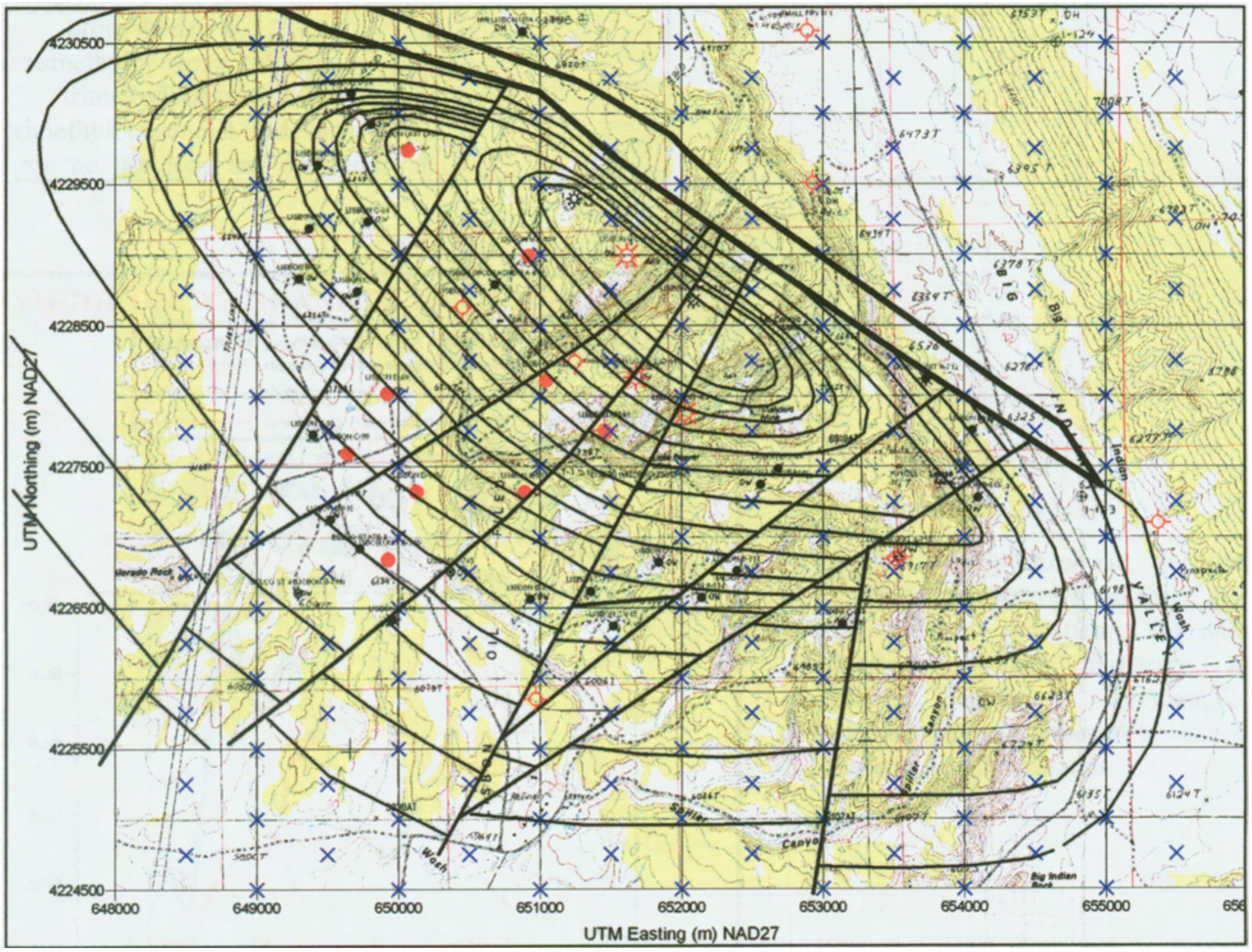


Figure 20. Initial planned sample grid (blue Xs represent sample locations; red circles and dots represent well locations) for the surface geochemical survey over Lisbon field, San Juan County, Utah. Shallow soils were collected at 1500-foot intervals over an area of 16 square miles.

Laboratory Analysis

The soil samples will be prepared (dried, sieved to <63 microns, thermally desorbed) and the headspace gas will be analyzed using Direct Geochemical's proprietary techniques to 40 hydrocarbon compounds in the C_1-C_{12} range, 53 major and trace elements, and seven anion species (table 3). In addition to previously tested techniques, Synchronous Scanned Fluorescence analysis (five fluorescence intensities at specific wavelengths) will also be applied to solvent extracts (for heavy aromatic compounds) of the soil samples to match seepage with produced oil at Lisbon (table 3). Oils with different gravities fluoresce at different wavelengths according to the number of contained aromatic ring compounds as shown by the examples in figure 21.

Interpretation and Mapping

The data will be compiled in spreadsheets for interpretation purposes. Sample results will be plotted and contoured to identify any surficial geochemical anomalies. The field and

Table 3. Analytes reported by four analytical methods.

C_l-C_{12} Hydrocarbons	Seven Anions	53 Major and Trace Elements	Synchronous Scanned Fluorescence
methane, ethane, ethene, propane, propene, i-butane, n-butane, butene, i-pentane, n-pentane, pentene, i-hexane, n-hexane, hexene, i-heptane, n-heptane, heptene, i-octane, n-octane, benzene, n-butylbenzene, cyclohexane, n-decane, n-dodecane, ethylbenzene, m-ethyltoluene, p-ethyltoluene, indane, naphthalene, n-nonane, n-propylbenzene, 1,2,4,5-tetramethylbenzene, toluene, 1,2,4-trimethylbenzene, 1,3,5-trimethylbenzene, n-undecane, m-xylene, p-xylene, and o-xylene.	fluoride, chloride, bromide, nitrite, nitrate, phosphate, sulfate	Ag, Al, As, Au, B, Be, Bi, Ca, Cd, Ce, Co, Cr, Cs, Cu, Fe, Ga, Ge, Hf, Hg, I, In, K, La, Li, Mg, Mn, Mo, Na, Nb, Ni, P, Pb, Pt, Pd, Rb, Re, S, Sb, Sc, Se, Sn, Sr, Ta, Te, Th, Ti, Tl, U, V, W, Y, Zn, Zr	Fluorescence intensities in the 250 to 500 nm range that correspond to condensate, medium-gravity oil, and low-gravity oil. Allows fingerprint matching with produced oils in the area.

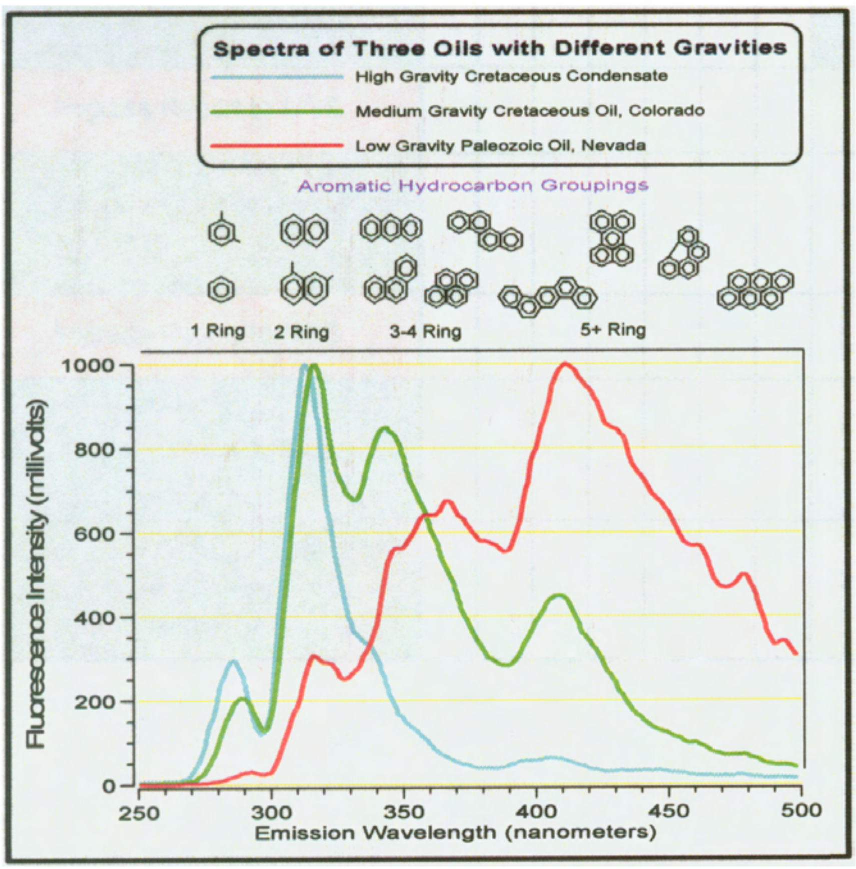


Figure 21. Synchronous Scanned Fluorescence spectra from three oils with different gravities. Courtesy of Direct Geochemical.

analytical precision will be evaluated through calculation of relative standard deviations (RSD's), and these RSD's compared with the total variance to ensure that between-site variance exceeds within-site variance. If these initial variance tests pass, then the data will be interpreted using standard methods. If the data distributions are significantly skewed, then they will be transformed into normality (logarithmic or other) following extreme outlier rejection. The variables may be normalized to Z-scores to better evaluate anomaly contrast in the data. Probability plots (cumulative frequency distributions) may also be used to find breakpoints in populations between anomalous and background conditions. The Z-scores of individual compounds or elements may be plotted as contour maps or proportional symbol plots.

Multivariate statistical techniques will be applied to attempt to discriminate between hydrocarbon microseepage over productive and non-productive areas. Factor and discriminant analysis will be used to measure the covariance of several variables in multidimensional space simultaneously.

Work to Date

Permission was obtained from the field operator, EnCana Oil & Gas (USA) Inc., and the U.S. Bureau of Land Management to conduct the surface geochemical sampling program in the Lisbon field area. A safety orientation was provided by EnCana at the Lisbon Gas Plant, and a hydrogen sulfide (H_2S) monitor was lent to the sampling crew. Some sampling sites were relocated and the grid adjusted farther to the west to avoid an H_2S pipeline in the field.

Ninety samples were collected around two productive oil wells in the oil leg, two gas wells in the gas cap, and two barren dry wells, (figures 22 and 23); 15 samples at each well site. The two oil wells are the Lisbon No. C-99 well (SW1/4SE1/4 section 9, T. 30 S., R. 24 E., SLBL&M), which has produced 502,759 bbls of oil (80,000 m^3) and 12.9 BCFG (0.37 BCMG), and the Lisbon No. D-716 well (SW1/4SE1/4 section 10, T. 30 S., R. 24 E., SLBL&M), which has produced 552,265 bbls of oil (88,000 m^3) and 10.1 BCFG (0.29 BCMG) (Utah Division of Oil, Gas and Mining, 2006). The two gas wells are the Lisbon No. C-910 well (SW1/4SE1/4 section 10, T. 30 S., R. 24 E., SLBL&M), which has produced 23,279 bbls of oil (3700 m^3) and 24.5 BCFG (0.69 BCMG), and the Lisbon No. D-810 (NW Lisbon USA No. A-2) well (NE1/4SE1/4 section 10, T. 30 S., R. 24 E., SLBL&M), which has produced 20,542 bbls of oil (3300 m^3) and 21.6 BCFG (0.61 BCMG) (Utah Division of Oil, Gas and Mining, 2006). The barren dry wells include one to the west of the field in the water leg (the No. 21-4 Federal, NW1/4NW1/4 section 21, T. 30 S., R. 24 E., SLBL&M) and the other is northeast of the field on the low side of the fault which parallels the structure (the No. 1 State-Small Fry, NE1/4NW1/4 section 2, T. 30 S., R. 24 E., SLBL&M).

EnCana provided produced gas composition data from the Lisbon No. C-910 well (table 4; figure 22). In addition, EnCana provided oil samples from Lisbon Nos. C-99 and D-716 wells for Synchronous Scanned Fluorescence analysis. The current field reservoir pressure is low due to nearly 50 years of production and current blowdown of the gas cap. Although production from the oil wells is relatively small (totaling 18 BOPD [3 CMPD), they currently represent the best in the field.

Initially, 26 samples were collected along two parallel lines from the western part of the grid (figure 23). By March 31, 2006, a total of 160 samples had been collected by the UGS along the sampling grid (figure 24). The 116 samples collected in mid-March have been dried and sieved, and aliquots are now being weighed out for chemical analyses.

Two main soil types were noted over the survey area. Soil on outcrop (figures 22 and 25) consists of patchy, shallow, microbiotic, lichen-covered, fine- to medium-grained sand (Munsell Color = 10YR 6/4). Vegetation on outcrops consists mainly of juniper and pinyon pine. The sandstone outcrops, mainly the Jurassic Navajo and Entrada Sandstones, have polygonal and parallel joints filled with sand and lichen. These joints may provide pathways

Figure 22. The Lisbon No. C-910 well, which produces 7 MMCF/D of low-Btu (≈ 670) sour gas with considerable amounts of N_2 and CO_2 (see table 4). Soils samples were collected from the ledge above the well pad to avoid contamination.

Table 4. Composition of produced gas from the Lisbon No. C-910 well. Courtesy of EnCana Oil & Gas (USA) Inc.

Component	Mol%
Methane	38.2829
Ethane	8.3868
Propane	2.4469
Isobutane	0.4025
n-Butane	0.2081
Isopentane	0.2207
n-Pentane	0.2725
Carbon Dioxide	28.775
Hydrogen Sulfide	1.0014
Nitrogen	18.8452
Helium	0.657
Hexanes Plus	0.5011

for hydrocarbon microseepage to the surface. In the flat valleys between outcrops, the soil profile is more continuous, deeper, and finer-grained than on outcrops (Munsell Color = 2.5YR 5/6). The soil consists mainly of silt and fine sand of eolian origin. Vegetation in the valleys mainly consists of sagebrush.

TECHNOLOGY TRANSFER

The UGS is the Principal Investigator and prime contractor for the Leadville Limestone project, described in this report. All maps, cross sections, lab analyses, reports, databases, and other deliverables produced for the project will be published in interactive, menu-driven digital (Web-based and compact disc) and hard-copy formats by the UGS for presentation to the petroleum industry. Syntheses and highlights will be submitted to refereed journals, as appropriate, such as the *American Association of Petroleum Geologists (AAPG) Bulletin* and

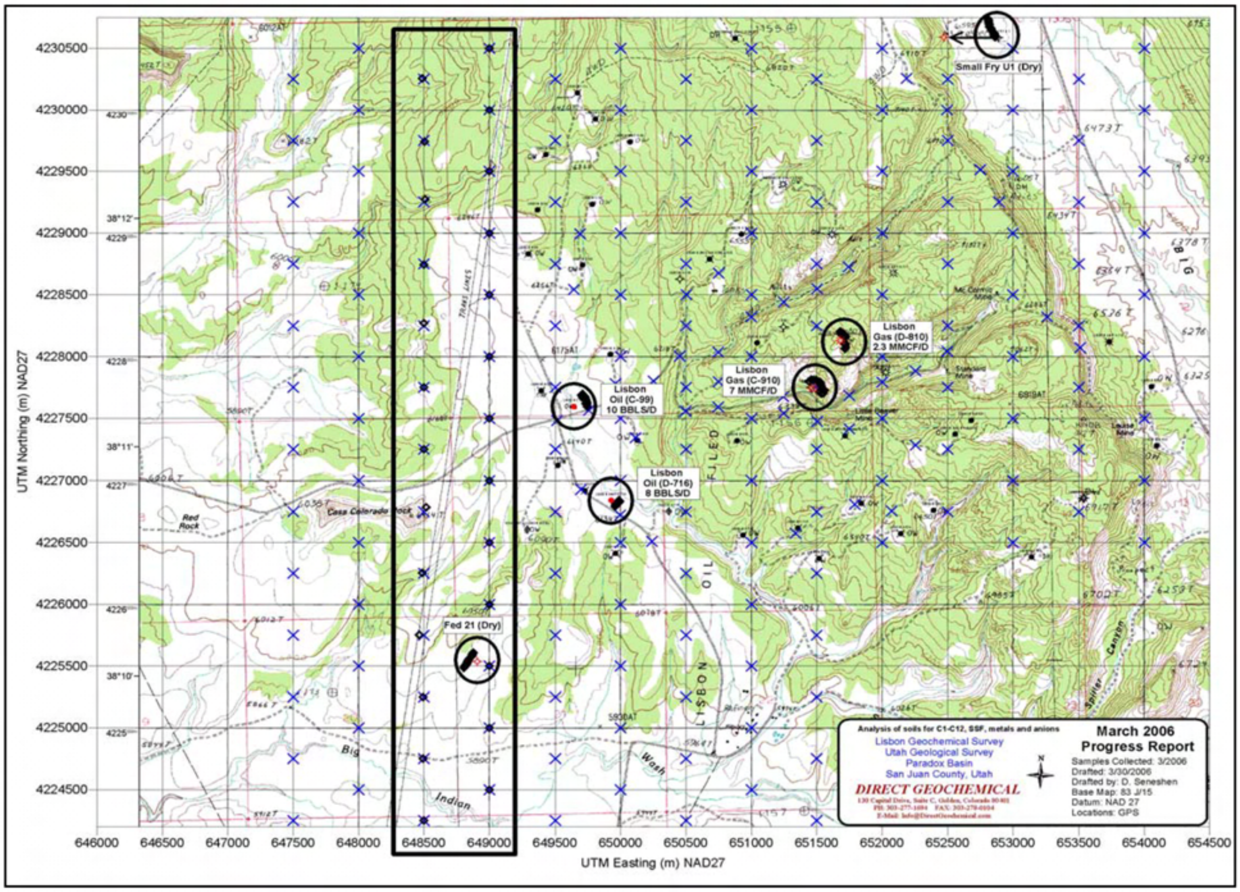


Figure 23. Revised sampling grid for the surface geochemical survey over Lisbon field. During the initial phase of the survey, a total of 116 samples were collected around oil, gas, and dry wells (15 at each of six wells [large black circles] – 90 samples) and along two lines in the western part of the grid (black rectangle) over the water leg (26 samples).

Journal of Petroleum Technology, and to trade publications such as the *Oil and Gas Journal*. This information will also be released through the UGS periodical *Survey Notes* and be posted on the UGS Paradox Basin project Web page.

The technology-transfer plan includes the formation of a Technical Advisory Board and a Stake Holders Board. These boards meet annually with the project technical team members. The Technical Advisory Board advises the technical team on the direction of study, reviews technical progress, recommends changes and additions to the study, and provides data. The Technical Advisory Board is composed of Leadville field operators and those who are actively exploring for Leadville hydrocarbons in Utah and Colorado. This board ensures direct communication of the study methods and results to the operators. The Stake Holders Board is composed of groups that have a financial interest in the study area including representatives from the State of Utah (School and Institutional Trust Lands Administration, and Utah Division of Oil, Gas and Mining) and the federal government (Bureau of Land Management). The members of the Technical Advisory and Stake Holders Boards receive all semi-annual technical reports, copies of all publications, and other material resulting from the study. Board members also provide field and reservoir data.

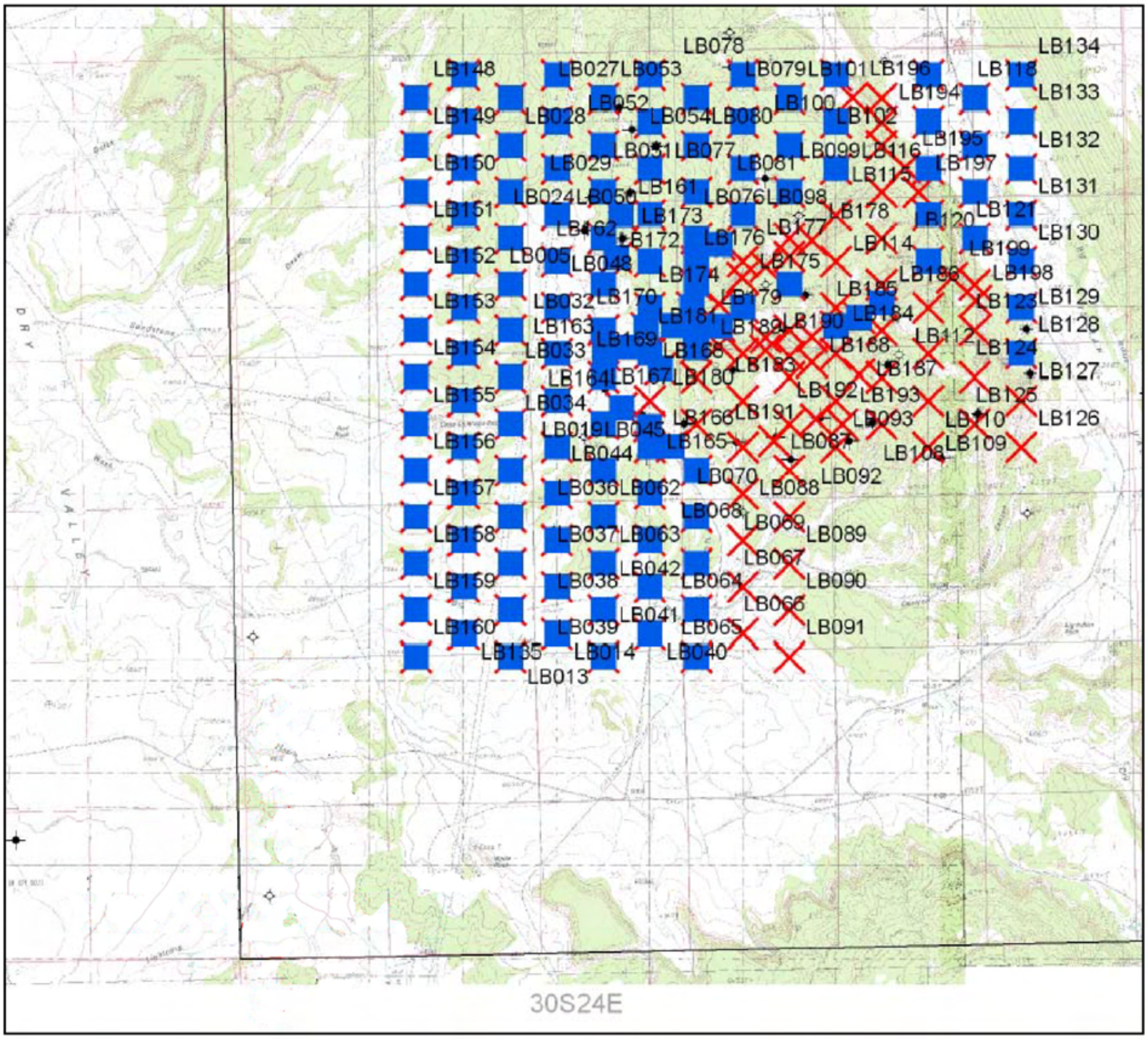


Figure 24. Samples collected (blue squares) as of March 31, 2006. Red Xs represent sites remaining for sample collection.

Utah Geological Survey *Survey Notes* and Web Site

The UGS publication *Survey Notes* provides non-technical information on contemporary geologic topics, issues, events, and ongoing UGS projects to Utah's geologic community, educators, state and local officials and other decision-makers, and the public. *Survey Notes* is published three times yearly. Single copies are distributed free of charge and reproduction (with recognition of source) is encouraged. The UGS maintains a database that includes those companies or individuals specifically interested in the Leadville project or other DOE-sponsored UGS projects. They receive *Survey Notes* and notification of project publications and workshops.

The UGS maintains a Web site on the Internet, http://geology.utah.gov. The UGS site includes a page under the heading *Oil, Gas, Coal, & CO_2*, which describes the UGS/DOE cooperative studies past and present (PUMPII, Paradox Basin [two projects evaluating the

Figure 25. Collection of shallow sandy soil from 4-inch depth on Navajo Sandstone outcrop.

Pennsylvanian Paradox Formation], Ferron Sandstone, Bluebell field, Green River Formation), and has a link to the DOE Web site. Each UGS/DOE cooperative study also has its own separate page on the UGS Web site. The Leadville Limestone project page, http://geology.utah.gov/emp/leadville/index.htm, contains (1) a project location map, (2) a description of the project, (3) a reference list of all publications that are a direct result of the project, (4) poster presentations, and (5) semi-annual technical progress reports.

Presentations

The following presentations were made during the reporting period as part of the technology transfer activities:

"Dolomitization of the Mississippian Leadville Reservoirs (with emphasis on Lisbon Field), Northern Paradox Basin, Utah and Colorado" by David E. Eby, at the Fort Worth Geological Society monthly meeting in Fort Worth, Texas, October 10, 2005.

"Dolomitization of the Mississippian Leadville Limestone, Paradox Basin, Utah" by Thomas C. Chidsey, Jr., David E. Eby, Craig D. Morgan, Kevin McClure, Joseph N. Moore, and John D. Humphrey, at the Geological Society of America Annual Meeting in Salt Lake City, Utah, October 19, 2005.

These presentations included discussions of the facies, petrography, and diagenesis, especially dolomite, of the Leadville Limestone in the Paradox Basin.

Project Publications

Chidsey, T.C., Jr., Eby, D.E., Morgan, C.D., McClure, K., Moore, J.N., and Humphrey, J.D., 2005, Dolomitization of the Mississippian Leadville Limestone, Paradox Basin, southeastern Utah [abs.]: Abstracts with Programs, Geological Society of America, v. 37, no. 7, paper 4-12.

Chidsey, T.C., Jr., Eby, D.E., and Humphrey, J.D., 2005, The Mississippian Leadville Limestone exploration play, Utah and Colorado: exploration techniques and studies for independents – semi-annual technical progress report for the period April 1, 2005 to September 30, 2005: U.S. Department of Energy, DOE/BC15424-4, 34 p.

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

1. The Mississippian Leadville Limestone is a shallow, open-marine, carbonate-shelf deposit. The Leadville has produced over 53 million barrels (8.4 million m^3) of oil from six fields in the Paradox fold and fault belt of the Paradox Basin, Utah and Colorado. Most Leadville oil and gas production is from basement-involved structural traps. All of these fields are currently operated by small, independent producers. This environmentally sensitive, 7500-square-mile (19,400 km^2) area is relatively unexplored. Only independent producers continue to hunt for Leadville oil targets in the region.

2. There is a systematic change in the chemistry of both the Mississippian/Devonian and Pennsylvanian brine systems from north to south through the Paradox Basin, and the associated counties. The Pennsylvanian-system brines are more saline than the Mississippian/Devonian-system brines. Piper and Stiff diagrams show that the brines from both systems are predominantly sodium-rich in nature, with some samples containing greater percentages of calcium and to a lesser extent magnesium. The Piper and Stiff diagrams also show that both brine systems are high in chloride with some samples being high in sulfate content. Bicarbonate is very low in both brine systems. The direction of ground-water movement in the Mississippian/Devonian and Pennsylvanian systems is generally southwestward toward the topographically low outcrop areas along the Colorado River in Arizona.

3. Lisbon field accounts for most of the Leadville oil production in the Paradox Basin. Its reservoir characteristics, particularly diagenetic overprinting and history, and Leadville facies can be applied regionally to other fields and exploration trends in the basin (including the recently discovered Lisbon South field to the southwest). Therefore, Lisbon field was selected as the case-study field for the Leadville Limestone project.

4. Surface geochemical surveys have proved to help identify areas of poorly drained or by-passed oil in other basins. Lisbon field is ideal for a surface geochemical survey because proven hydrocarbons underlie the area, sample sites are relatively easily accessible, and the surface geology is similar to the structure of the field. Lisbon field is the largest Leadville producer and is still actively producing oil and gas. The surface geology at Lisbon field consists of a major anticline along a large normal fault. Proving the success of relatively low-cost geochemical surveys at Lisbon field will allow independent operators to reduce risks and minimize impacts on environmentally sensitive areas while exploring for Leadville targets.

5. The geochemical survey consisted of collecting about 200 shallow soil samples at 1500-foot intervals (500 m) on a 16-square-mile (42 km^2) rectangular grid over and around the Lisbon field to map the spatial distribution of surface hydrocarbon anomalies. The sampling grid extends beyond the proven limits of Lisbon field to establish background readings. The area chosen sufficiently covers the oil-leg, gas cap, and background barren areas. In addition, samples were collected over oil, gas, and dry wells for analogue matching purposes and to refine the discriminant model for Lisbon field. The soils were placed and stored in airtight, Teflon-sealed glass soil jars to prevent hydrocarbon contamination during transport.

6. Ninety samples were collected around productive oil (two) wells in the oil leg, gas (two) wells in the gas cap, and two barren dry wells; 15 samples at each well site. By March 31, 2006, a total of 160 samples had been collected by the UGS along the sampling grid. Samples are being dried and sieved, and aliquots are now being weighed out for chemical analyses for 40 hydrocarbon compounds in the C_1-C_{12} range, 53 major and trace elements, seven anion species, and for Synchronous Scanned Fluorescence analyses. Sample results will be plotted and contoured to identify any surficial geochemical anomalies.

7. Two main soil types were noted over the survey area. Soil on outcrop consists of patchy, shallow, microbiotic, lichen-covered, fine- to medium-grained sand. Sandstone outcrops have polygonal and parallel joints filled with sand and lichen. In the flat valleys between outcrops, the soil profile is more continuous, deeper, and finer-grained than on outcrops, consisting mainly of silt and fine sand of eolian origin.

8. Joints in the Navajo and Entrada Sandstones may provide pathways for hydrocarbon microseepage to the surface. We recommend expanding the sampling program to collect the sand and lichen from the joints for hydrocarbon and elemental analysis over barren and productive parts of Lisbon field.

9. The recently discovered Lisbon South field has similar geology to Lisbon field, both in terms of structure and a Leadville reservoir. It consists of two producing wells, primarily gas and condensate, along with barren dry wells off structure. However, the Lisbon South field is still near original reservoir pressure and therefore hydrocarbon microseepage to the surface may be more significant than at Lisbon field to the northeast. We recommend an additional expansion of the surface geochemical survey to include this new field and the surrounding area.

ACKNOWLEDGMENTS

Funding for this research was provided as part of the Advanced and Key Oilfield Technologies for Independents (Area 2 – Exploration) Program of the U.S. Department of Energy, National Petroleum Technology Office, Tulsa, Oklahoma, contract number DE-FC26-03NT15424. The Contracting Officer's Representative is Virginia Weyland. Support was also provided by Eby Petrography & Consulting, Inc., Littleton, Colorado, Direct Geochemical, Golden, Colorado, ST Oil Company, Denver, Colorado, the Utah School and Institutional Trust Lands Administration, and the Utah Geological Survey (UGS).

Gas analyses and oil samples as well as surface access in Lisbon field were provided by Encana Corp. James Parker and Sharon Wakefield of the UGS drafted figures and maps; Cheryl Gustin, UGS, formatted the manuscript. This report was reviewed by David E. Tabet and Michael D. Hylland of the UGS.

REFERENCES

Breit, G.N. (compiler), no date, Produced waters database: U.S. Geological Survey: Online, <http://energy.cr.usgs.gov/prov/prodwat/>, accessed May 2003.

Clark, C.R., 1978, Lisbon, San Juan County, Utah, *in* Fassett, J.E., editor, Oil and gas fields of the Four Corners area: Four Corners Geological Society, v. II, p. 662-665.

Doelling, H.H., 2000, Geology of Arches National Park, Grand County, Utah, *in* Sprinkel, D. A., Chidsey, T.C., Jr., and Anderson, P.B., editors, Geology of Utah's parks and monuments: Utah Geological Association Publication 28, p. 11-36.

Gwynn, J.W., 1995, Resistivities and chemical analyses of selected oil and gas field, water well, and spring waters, Utah: Utah Geological Survey Circular 87, 142 p.

Hanshaw, B.B., and Hill, G.A., 1969, Geochemistry and hydrodynamics of the Paradox Basin region, Utah, Colorado, and New Mexico, *in* Angino, E.E., and Billings, G.K., editors, Geochemistry of subsurface brines: Chemical Geology, v. 4, no. 1/2, p. 263-294.

Harry, D.L., and Mickus, K.L., 1998, Gravity constraints on lithospheric flexure and the structure of the late Paleozoic Ouachita orogen in Arkansas and Oklahoma, south-central North America: Tectonics, v. 17, no. 2, p. 187-202.

Hintze, L.F., 1993, Geologic history of Utah: Brigham Young University Geology Studies Special Publication 7, 202 p.

Hintze, L.F., Willis, G.C., Laes, D.Y.M., Sprinkel, D.A., and Brown, K.D., 2000, Digital geologic map of Utah: Utah Geological Survey Map 179DM, 17 p., scale 1:500,000.

Howells, Lewis, 1990, Base of moderately saline ground water in San Juan County, Utah: Utah Department of Natural Resources Technical Publication 94, 35 p.

Huntoon, P.W., 1979, The occurrence of ground water in the Canyonlands area of Utah, with emphasis on water in the Permian section, *in* Baars, D.L., editor, Permianland: Four Corners Geological Society Guidebook, 9th Annual Field Conference, p. 39-46.

Johnson, C.F., 1970, Top of structure of the Leadville Limestone, Lisbon field: unpublished map, Union Oil Company of California files.

Kluth, C.F., 1986, Plate tectonics of the Ancestral Rocky Mountains, *in* Peterson, J.A., editor, Paleotectonics and sedimentation in the Rocky Mountain region, United States: American Association of Petroleum Geologists Memoir 41, p. 353-369.

Kluth, C.F., and Coney, P.J., 1981, Plate tectonics of the Ancestral Rocky Mountains: Geology, v. 9, p. 10-15.

Merin, I.S., and Segal, D.B., 1989, Diagenetic alteration of Wingate Formation – possible indicators of hydrocarbon microseepage, Lisbon Valley, Utah: Journal of Geology, v. 97, p. 719-734.

Parker, J.W., and Roberts, J.W., 1963, Devonian and Mississippian stratigraphy of the central part of the Colorado Plateau: Four Corners Geological Society, 4th Field Conference Guidebook, p. 31-60.

Petroleum Information, 1984, Paradox Basin–unravelling the mystery: Petroleum Frontiers, v. 1, no. 4, p. 22.

Schumacher, D., and LeSchack, L.A., (editors), 2002, Surface exploration case histories – applications of geochemistry, magnetics, and remote sensing: American Association of Petroleum Geologists Studies in Geology 48, 500 p.

Segal, D.B., and Merin, I.S., 1989, Successful use of Landsat Thematic Mapper Data for mapping hydrocarbon microseepage-induced mineralogic alteration, Lisbon Valley, Utah: Photogrammetric Engineering and Remote Sensing, v. 55, no. 8, p. 1137-1145.

Segal, D.B., Ruth, M.D., and Merin, I.S., 1986, Remote detection of anomalous mineralogy associated with hydrocarbon production, Lisbon Valley, Utah: The Mountain Geologist, v. 23, no. 2, p. 51-62.

Seneshen, D.M., Viellenave, J.H., and Fontana, J.V., 2006, The surface geochemical expression of carbonate-hosted hydrocarbon reservoirs and faults in New York, Ohio, Nevada, and Utah [abs.]: American Association of Petroleum Geologists Annual Convention Abstracts, v. 15, p. 98.

Smith, K.T., and Prather, O.E., 1981, Lisbon field – lessons in exploration, *in* Wiegand, D.L., editor, Geology of the Paradox Basin: Rocky Mountain Association of Geologists Guidebook, p. 55-59.

Smouse, DeForrest, 1993, Lisbon, *in* Hill, B.G., and Bereskin, S.R., editors, Oil and gas fields of Utah: Utah Geological Association Publication 22, non-paginated.

Spangler, L.E., Naftz, D.L., and Peterman, Z.E., 1996, Hydrology, chemical quality, and characterization of salinity in the Navajo aquifer and near the Greater Aneth oil field, San Juan County, Utah: U.S. Geological Survey Water-Resources Investigations Report 96-4155, 90 p.

Stevenson, G.M., and Baars, D.L., 1987, The Paradox—a pull-apart basin of Pennsylvanian age, *in* Campbell, J.A., editor, Geology of Cataract Canyon and vicinity: Four Corners Geological Society, 10th Field Conference, p. 31-55.

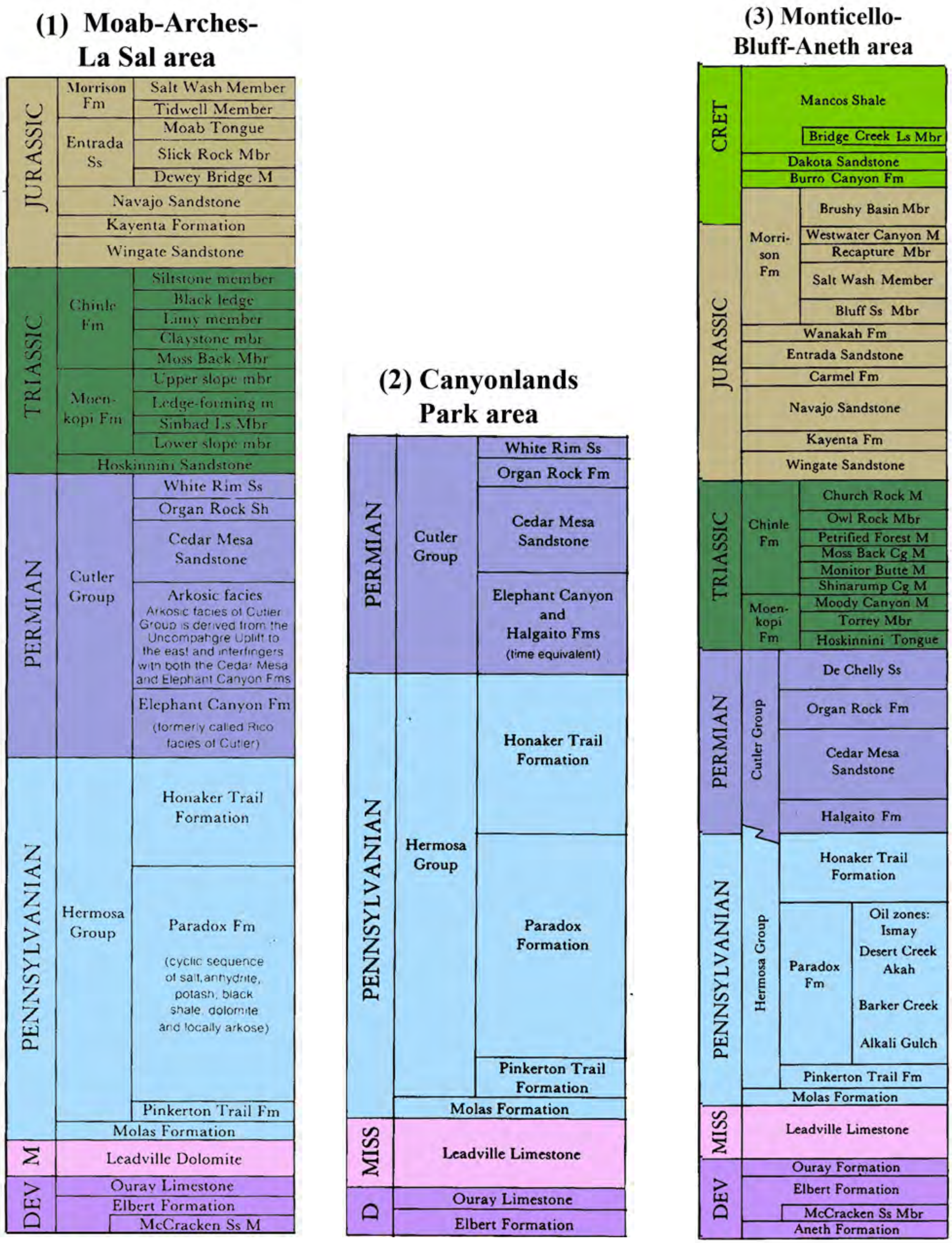
Utah Division of Oil, Gas and Mining, 2006, Oil and gas production report, March: Online, <http://www.ogm.utah.gov/oilgas/PUBLICATIONS/Reports/PROD_book_list.htm>, accessed July 25, 2006.

Wood, J.R., Bornhorst, T.J., Chittick, S.D., Harrison, W.B., Quinlan, W., and Taylor, E., 2001, Using recent advances in 2D seismic technology and surface geochemistry to economically redevelop a shallow shelf carbonate reservoir – Vernon field, Isabella County, MI - annual report, March 20, 2000-March 20, 2001: U.S. Department of Energy, DOE/BC/15122-1, 25 p.

Wood, J.R., Bornhorst, T.J., Harrison, W.B., and Quinlan, W., 2002, Using recent advances in 2D seismic technology and surface geochemistry to economically redevelop a shallow shelf carbonate reservoir – Vernon field, Isabella County, MI - annual report, March 21, 2001-March 20, 2002: U.S. Department of Energy, DOE/BC/15122-2, 20 p.

APPENDIX

STRATIGRAPHIC SECTIONS



Modified from Hintze, 1993